Use of Electroplated Chromium in Gun Barrels

Michael J. Audino, US Army RDECOM-ARDEC-Benet Laboratories

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State of the Practice

Current and developing weapon systems have gun tubes that use electrodeposited chrome as a protective finish on their interior bore surface. This coating protects the bore surface against the harsh environment of the hot propellant gases, and the mechanical effects of the projectile thereby increasing the life of the gun tube. However, chrome is a heavy metal which is deposited onto the tube surface using aqueous electro-deposition. The chromic acid used in the deposition process is a hazardous substance because it contains hexavalent chrome. Hexavalent chromium is a major problem when it comes to environmental pollution prevention efforts and worker safety. Hexavalent chromium, in the aqueous liquid and misting forms, is a known carcinogen which is extremely expensive to dispose of because of its toxic nature. Agencies that plate with chromium spend hundreds of thousands of dollars on environmental waste removal. These agencies incur enormous costs protecting or minimizing employee exposure to aqueous or gaseous chromic acid. In response to this hazard, OSHA has recently reduced the current Permissible Exposure Limit (PEL) established for water soluble chrome VI compounds from the current 50 micrograms per cubic meter to 5 micrograms per cubic meter.

The use of electrodeposited chromium in gun barrels is widespread. Table 1 provides a listing of all currently-fielded, Army-produced large caliber guns. Note that all but one gun barrel (105mm M68A1E8) uses chrome plating in some capacity. Table 2 provides a listing of Navy-produced large caliber guns. Chrome is used as bore protection in those systems as well. Finally, Table 3 provides a listing of all tri-service medium caliber guns that use chrome plating. It is interesting to note that approximately 40,000 chrome plated medium caliber guns are planned for production between 2004 and 2013. The location of gun plating operations varies with service and caliber. Navy large caliber guns are produced by BAE, North America (formerly United Defense, LP) while all tri-service medium caliber guns are produced by either General Dynamics (Saco, ME) or Alliant Technologies (Mesa, AZ) . All Army large caliber guns are produced by the Army at Watervliet Arsenal located in upstate New York.

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Standard Form 298 (Rev. 8-98)
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Table 1: Army Large Caliber Cannon

Gun Type	Weapon System	Chrome Plated Components
Fielded Systems		
120mm M256	M1A2 Main Battle Tank	Chamber & Bore
155mm M284	M109A6 SP Howitzer	Chamber, Split & Inner Rings, Spindle
155mm M199	M198 Towed Howitzer	Chamber, Split & Inner Rings, Spindle
105mm M20	M119 Towed Howitzer	Chamber, Split & Inner Rings, Spindle
105mm M68A1E8	Stryker	None
120mm M298	M120 Towed / M121 (1064 APC)	Elevation-Traverse Mechs
81mm M29A1	M29A1 / M125 APC	Elevation-Traverse Mechs
81mm M253	M252 Ext. Range Mortar	Elevation-Traverse Mechs / Bi-Pod
60mm M225	M224 Light Company Mortar	Elevation-Traverse Mechs / Bi-Pod
Systems Under Development		
120mm XM360	MCS	Chamber & Bore
155mm XM324	NLOS-C	Chamber, Split & Inner Rings, Spindle
120mm XM325	NLOS-M	TBD
155mm M776	M777 Towed Howitzer	Chamber, Split & Inner Rings, Spindle

Table 2: Navy Large Caliber Cannon

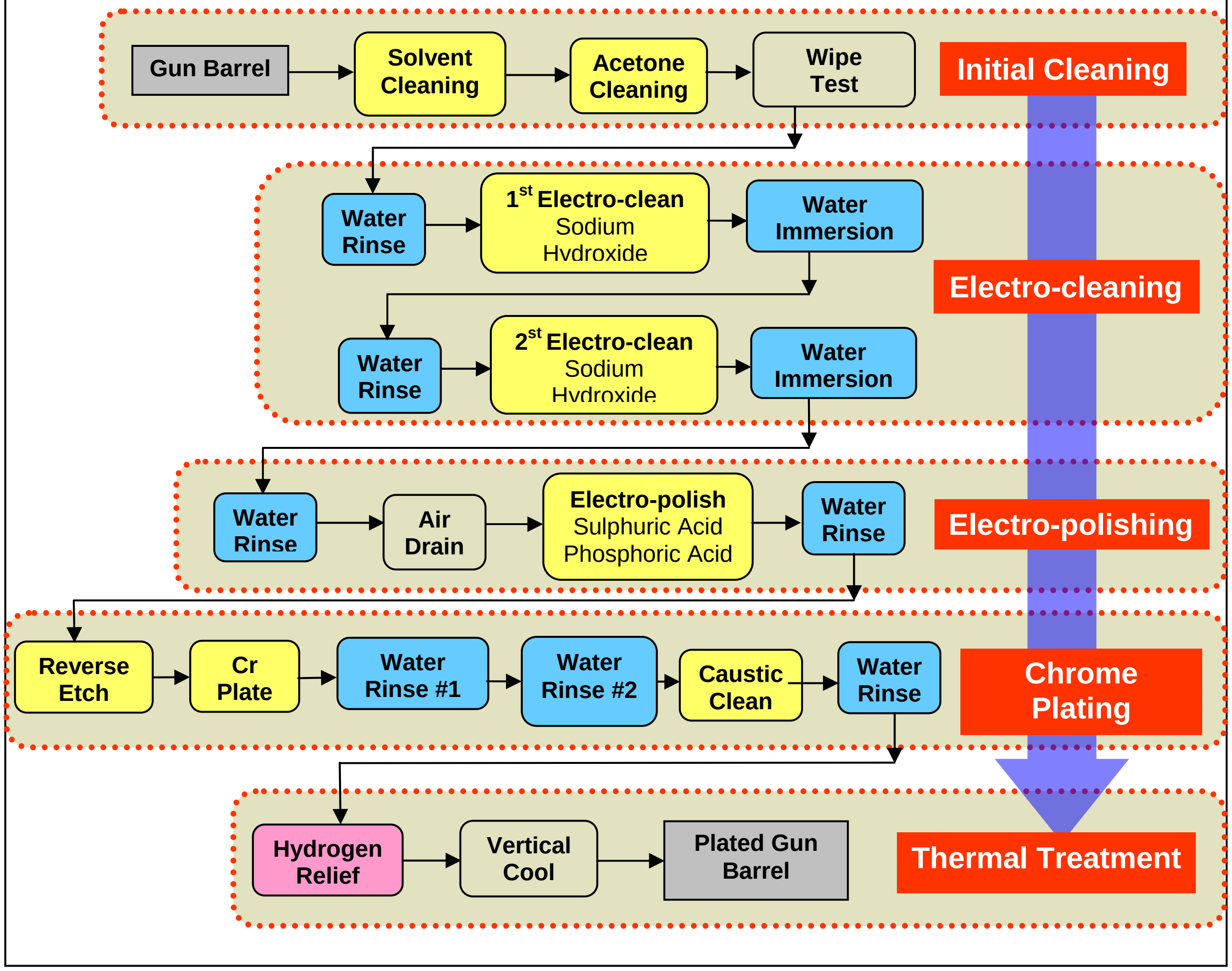
Gun Type	Weapon System	Chrome Plated Components
Fielded Systems		
76mm Mk75	Perry-Class Frigate	Mk33 Liner Chamber & Bore
5” Mk45 (54 cal)	Ticonderoga, Burke, Spruance-class ships	Chamber & Bore
5” Mk45 Mod4 (62 cal)	Ticonderoga, Burke-class ships	Chamber & Bore

Table 3: Tri-Service Medium Caliber Guns

CALIBER (mm)	GUN BARREL	ARMAMENT SYSTEM	WEAPON SYSTEM	WEAPON SYSTEM NAME
20mm	GAU-4	Vulcan	F/A-18, F-15, F-16, F-22A, F-14A/B/D	Hornet, Eagle, Falcon, Raptor, Tomcat Fighting Aircraft
		3-Barrel Gatling Gun	AH-1W	Super Cobra Helicopter
20 mm	M61A1	Mk15, Phalanx CIWS	Kitty Hawk, Nimitz, Ticonderoga, Spruance, Burke, Perry, Wasp, Tarawa-class ships	Carriers, Cruisers, Destroyers, Frigates, Landing and Amph. Assault Ships
20 mm	XM-301	3-Barrel Gatling Gun	RAH-66	Comanche Helicopter
25 mm	GAU-12		F-35, AV-8B, AC-130H/U	Joint Strike Fighter, Harrier, Gunship
25 mm	M242	Bushmaster	M2/M3, LAV-25, Ticonderoga, Perry, Cyclone, & San Antonio-class ships	Bradley FV, LAV, Cruiser, Frigate, Coastal Patrol, Docking Ship
30 mm	GAU-8/A	7-Barrel Gatling Gun	A-10	Thunderbolt II Air Support Aircraft
30 mm	M230	Chain Gun	AH-64	Apache Helicopter
30 mm	Mk44	Bushmaster II	EFV, LPD-17, MH-53E. AC130	Amph Assault Vehicle, Amph. Ship, Helicopter, Gunship

All chrome plated barrels (listed above) are plated using standard immersion plating processes. There are some slight variations within the processes but the basics remain constant. Figure 1 illustrates the plating process for Army large caliber guns. The plating of Navy large caliber guns and tri-service medium caliber guns approximates this same immersion process.

Figure 1: Basic Gun Barrel Electroplating Process



Requirement

The principal performance requirement of a gun barrel bore coating is to prevent premature wear and erosion of the gun barrel resulting in a shorter service life. Wear and erosion shortens gun life through both ballistic inaccuracy and through the acceleration of mechanical fatigue failure. In the case of ballistic inaccuracy, wear and erosion of the bore surface causes bore enlargement through the removal of bore material. The removal of this material provides room for propelling charge gasses to pass the cartridge (or projectile) while it is still in-bore. As a result, the cartridge (or projectile) leaves the gun with a lower muzzle velocity resulting in target dispersion. As far as mechanical fatigue life reduction is concerned, bore coatings can provide thermal protection that can prevent substrate transformation (untempered martensite) and the susceptibility to crack formation in the altered layer.

The current erosion mechanism of chrome plated large caliber guns starts during the manufacturing process. After the barrel has been plated it must be exposed to a hydrogen bake-out process. During this process, the barrel is heated so that hydrogen, provided during the plating process, can be liberated. The liberation of hydrogen and other non-chrome contaminants causes a volumetric reduction of the chrome layer. Tensile stresses build up during the post-hydrogen relief cool-down period as the coating volume attempts to contract. Since the coating is adhered to the barrel, the coating cannot freely contract. The stresses are partially relieved through the development of small cracks (called micro-cracks) in the coating. Once the barrel is fielded, these “micro-cracks” provide pathways for the propelling charge gasses to reach and attack the steel substrate. When this happens, oxides and carbides are produced in the steel substrate just underneath the chromium layer. These oxides and carbides further reduce the melting point of the steel substrate allowing material to be removed through the action of “gas wash”. As this material departs the gun, it takes chromium with it revealing more of the unprotected substrate. With more unprotected substrate available to the gas stream, the erosion process dramatically increases. The resulting roughened surface causes an increase in heat transfer coefficient allowing an even greater heat load to the gun barrel. Further cracking of the chromium coating (beyond the as-manufactured micro-cracks) also occurs as a result of the thermal cycling of the gun barrel. During firing, the surface of the gun bore reaches 1400C within a few milliseconds. A steep thermal gradient develops resulting in dramatic shear stresses at the coating-substrate interface. These stresses aid in the chrome removal process. As the bore surface temperature rises, the chrome coating wants to expand and the “islands” of chrome (separated only by the micro-cracks produced during deposition) push against each other with the edges of these “islands” lifting up. Upon cool-down, these edges can be removed by the passage of the round. Again, this roughened surface causes an increase in heat transfer coefficient allowing an even greater heat load to the gun barrel.

As a result of the identification and understanding of this erosion mechanism, the ideal requirements for a chromium replacement coating are listed below (Table 4). Many of these requirements can also, potentially, yield a performance increase.

Table 4.

MATERIAL CHARACTERISTIC	CRITERIA
Melting Point	Cr (1875 C) or better (propellant growth potential)
Elastic Modulus	Compatible with substrate (low surface crack densities)
YS at Elevated Temps	High
Fracture Toughness	High
Hot Hardness	High (appropriate)
Chemical Resistance	High
Coefficient of Thermal Exp.	Compatible with substrate
Thermal Conductivity	Low
Reaction w/ Rotating Band	Inert (Indirect Fire)
Phase Transformations	None
Propensity to Cracking	Low

PROCESS CHARACTERISTIC	CRITERIA
Deposition Temperature	Less than 357C (post autofrettage thermal soak limit)
Deposit Rate	1 mil of coating material per hour
Surface Finish	Equal or better than 32 RMS at deposition
Deposition Length	58 Calibers or greater (for artillery guns)
Hazardous Impacts	None or limited

Most of the aforementioned requirements are obvious but a few require further clarification. It is important that the elastic modulus of the coating (or coating system) be compatible with the substrate. Very hard coatings with a high modulus will not effectively transfer the firing loads to the bulkier substrate. In an attempt to carry the load, they will fail by cracking resulting in an early onset of erosion via the mechanism described above. Coatings with a modulus comparable to the substrate will effectively transfer the load to the substrate and remain crack-free longer that higher modulus materials.

Preventing phase transformation is important as well. These transformations are usually accompanied by volumetric changes which, again, can produce stresses that result in the cracking of the coating.

Coating deposition temperature is a vital concern for large caliber guns. Large caliber guns are autofrettaged. This process involves forcing an oversized mandrel through the bore of the gun. By doing so, a portion of the barrel wall is plastically deformed. Upon removal of the mandrel, the remaining elastic wall material attempts to return to its original dimension. The deformed (plastic) material resists the return to original dimensions and, as a result, is forced into a state of beneficial compressive residual hoop stress. This “preloading” effect provides the barrel with a higher load carrying capability and a longer fatigue life. After autofrettage, the gun barrel is thermally soaked at 357C to help “normalize” these beneficial residual stresses. As a result, any subsequent operation in the manufacture of the gun barrel that includes heating above 357C (bulk) will result in a reduction of these beneficial residual stresses, thus, weakening the barrel. Because large caliber barrels are designed “at margin” for the purposes of weight savings, exceeding this bulk temperature threshold by as little as 25C can cause the barrel to permanently deform when firing high energy cartridges.

The primary specifications used in the chrome plating of gun barrels are QQ-C-320 and Mil-Std-171. In addition, Army large caliber guns are chrome plated using Special Process Procedure SPP-0001. These standards establish the minimum requirements for finishing, and otherwise treating, metal and wood surfaces, and serve as a general guide to the selection of suitable finishing materials, procedures, and systems.

Chromium exposure in the plating of gun barrels occurs at a number of locations. All Army large caliber guns are produced by the Army at Watervliet Arsenal located in upstate New York. Sixteen (16) chrome plating immersion tanks exist at Watervliet. Navy large caliber guns are produced by BAE, North America (formerly United Defense, LP) at their Louisville, KY plant formerly known as Louisville Arsenal. Most tri-service medium caliber guns are produced by either General Dynamics (Saco, ME) or Alliant Technologies (Mesa, AZ) .

Drivers and Barriers

The key policy and/or regulatory drivers for the reduction/elimination of hexavalent chromium processes are:

- Clean Air Act (CAA)
- Clean Water Act (CWA)
- Comprehensive Environmental Response, Compensation and Liability Act
- Toxic Substances Control Act (TSCA)
- Occupational Safety and Health Act (OSHA)
- State and/or local regulations
- Resource Conservation and Recovery Act (RCRA)
- Pollution Prevention Act (PPA)
- Executive Order (EO) 12873 - Federal Acquisition, Recycling, and Waste Prevention, October 20, 1993
- Executive Order (EO) 12856 - Federal Compliance with Right-to-Know Laws and Pollution Prevention Requirements

Large caliber gun performance requirements associated with the Future Combat System's (FCS) Mounted Combat System (MCS) (next generation tank) call for a barrel wear life of 1500 rounds. This requirement encompasses the use of both Line-of-Sight (LOS) munitions and Beyond-Line-of-Sight (BLOS) munitions. Current chrome plated barrel life for the 120mm tank gun is at 280 rounds. The resulting performance gap will require bore protection technology that exceeds the current capabilities of chrome plating. As a result, drivers for chromium replacement in large caliber barrels are based on hazmat and cost reductions as well as a desire for performance enhancement.

The FCS Operational Requirements Document does not currently specify a precise wear life performance requirement for medium caliber guns planned for FCS platforms. Because of the desire to reduce system weight, planned stores of ammunition in the vehicle will be less. As a result, there is not a strong interest in increasing medium caliber wear life since changes in warfighting doctrine for the FCS's Expeditionary Fighting Vehicle (which uses the 30mm Mk44) will prevent the firing of medium caliber guns in a sustained burst mode. Consequently, wear and erosion issues are considered to be minimal. There are those that have serious concerns with this approach but for now, that is the plan. As a result, drivers for chromium replacement in medium caliber barrels are based on hazmat and cost reductions only will little interest in increased performance.

Potential barriers exist for the implementation of chrome plating alternatives in guns. As previously stated, Army large caliber guns are produced at Watervliet Arsenal which is owned and operated by the Army. Changes to the tech data package and implementing the process into production can happen relatively smoothly. On the other hand, medium caliber guns are produced by industry. Some medium caliber gun TDPs are managed by the contractor. This can, potentially, present some conflicts should the proposed environmentally friendly solution be less cost effective than the existing process. Unless the proposed solution provides economic benefit to the gun manufacturer, it could be difficult to have the solution implemented.

Finally, the most critical barrier of all is the potential inability to achieve equivalent performance with a selected alternative. This will be discussed further, below.

Adoption of Alternatives

To date, chromium plating alternatives have not been adopted into the production of guns. The primary and most widely-used cannon bore protection technology currently used for DoD guns is chromium plating. Approximately twenty (20) fielded and proposed gun designs, mounted on approximately forty (40) (+/-) weapons platforms, use chrome plating as bore protection. On average, between 2,000 and 4,000 Cr-plated gun barrels are produced each year for DoD.

The primary reason for the lack of implemented chrome replacement technologies is that, to date, there are no technologies that can produce the equivalent gun performance that chrome plating provides. The current Army large caliber chrome replacement program is getting closer to producing a solution with cylindrical magnetron sputtering technology. Recent live fire tests of coated gun barrels have produced extremely encouraging results. Initial efforts are underway for some medium caliber guns through the exploitation of explosive cladding technology. The current SERDP program, WP#1426, is investigation the cladding of a number of environmentally friendly materials. Nevertheless, as of this writing, there has yet to be an environmentally friendly gun coating alternative (that provides equivalent or better gun performance) implemented into a production environment. Table 5, below, provides a brief summary of processes evaluated-to-date.

Table 5	**PROCESSES**						
MAJOR FUNCTIONAL REQUIREMENTS	Electro-deposition via Molten Salts	Plasma Spray	CVD	Ion based Processes	Explosive Bonding	Electro-plated Chrome	Magnetron Sputtering
Autofrettage Stresses Protected (Lg Cal ONLY)				X		X	X
No Post-process Surface Finish Req	X			X		X	X
Acceptable Deposition Rate	X	X	X		X	X	X
Proper Process Aspect Ratio			X			X	X
Accept Dim. and Densities over 50 cal (Lg Cal Only)						X	X
Acceptable Adhesion	X				X	X	TBD
Accommodates Rifled Barrels	X		X			X	
Dry Process		X	X	X	X		X
Eliminate Hazardous Materials		X		X	TBD		X
Eliminate Air / Water Contamination				X	TBD		X

Remaining Needs

As mentioned above, work to develop an alternative coating on medium caliber guns has recently begun under SERDP program WP#1426. Nominal technical goals of the program include the reduction of inter-metallic formation at the interface, increased cladded material hardness to accommodate projectile engraving loads, and producibility. As the program develops further, remaining needs will become more obvious.

The Army's large caliber gun coating program is providing very encouraging data as a result of recent live-fire tests at Aberdeen Test Center (ATC). Guns coated with tantalum (applied by sputtering technology) have survived approximately 100 rounds (goal is 260) of high energy ammunitions without reaching the condemnation criteria of the gun. Testing was halted due to unrelated gun issues. Further live-fire testing is planned for summer 2006. A pre-production facility has already been built at Watervliet Arsenal for eventual transition to the production line of large caliber guns.

The program has eleven major technical metrics. They are:

Coating Morphology
Coating Phase
Hardness
Thermal Shock Resistance
Adhesion / Cohesion
Distribution over Length and around ID
Deposition Rate
Coating Thickness
Surface Finish
Onset of Erosion
Weapon Service Life

Of these, nine have been successfully met with adhesion and weapon service life being the remaining challenges. Obviously, these metrics are related since the current coating failure mode (after 100+ rounds) is sporadic disbonding. Great strides have been made in this area since only two years ago 70% coating loss was seen after only 20 rounds. Less than 15% coating loss is now realized after over 100 rounds. Increases in adhesion are expected to foster increased weapon service life. As a result, the recent focus of the program has been applied to cleaning and other surface preparation technologies. Being a PM funded effort, there is resistance to funding the basic experimentation necessary to develop these surface preparation techniques. As a result, the remaining challenge before this technology can become a production process for large caliber barrels is more development of pre-sputtering surface preparation technologies. This basic technological need is summarized in the following focus areas:

Focus Area: Evaluation of a cold cathode on CMS performance
Justification: Currently use a hot cathode for CMS which is atypical in industry. Use of a cold cathode will increase deposition rate, reduce coatings contamination, and facilitate scale-up of CMS technology.
Cost: $500K (R.O.M. est.)

Focus Area: Post Processing of CMS coatings to improve adhesion
Justification: To provide local heating to promote diffusion bonding and improved adhesion
Cost: $500-1000K (R.O.M. est.)

Focus Area: Reactive chemical cleaning
Justification: To utilize low voltage hydrogen plasma chemical cleaning to mitigate issues with recontamination of material from current plasma cleaning technique, to improve adhesion, and to facilitate scale up of CMS process.
Cost: $300K (R.O.M. est.)

Conclusion

To date, chromium plating alternatives have not been adopted into the production of guns. The primary and most widely-used cannon bore protection technology currently used for DoD guns is chromium plating. Approximately twenty (20) fielded and proposed gun designs, mounted on approximately forty (40) (+/-) weapons platforms, use chrome plating as bore protection. On average, between 2,000 and 4,000 Cr-plated gun barrels are produced each year for DoD.

Two technologies have emerged that show promise in the production of guns. Cylindrical Magnetron Sputtering (aka magnetized PVD) is being matured by the Army for large caliber, smooth-bore guns. The Navy is starting to develop the same technology (with slight modification) for its rifled, ship-mounted large caliber guns. The Army is starting to develop explosive cladding technology for tri-service medium caliber guns while the Navy is also looking at this technology for its rifled, ship-mounted large caliber guns. At the moment, only the Army's Watervliet Arsenal has completed construction of a production-capable facility for depositing environmentally-friendly gun bore coatings.

Gun Barrels

DoD Metal Plating Workshop

“Products That Radically Redefine Warfare, Enabling the American Warfighter to Dominate the Battlefield”

22 May 2006

Michael Audino
Benet Laboratories
US Army Armaments RDE Center
RDECOM

ARMY LARGE CALIBER ARMAMENT SYSTEMS


120mm M1A2 ABRAMS


120mm FCS-MCS


155mm FCS-NLOS-C


155mm M109A6 PALADIN


155mm XM777


105mm M119


81mm M253


155mmM199


120mm M298


60mm M225


81mm/120mm M29A1/M298 Carrier-mounted Mortars

“Provide Innovative Armaments Solutions for Today and Tomorrow”

ARMY LARGE CALIBER ARMAMENT SYSTEMS

Gun Type	Weapon System	Gun Mfr’er	System Mfr’er/Assy	Cr-Plating
Fielded Systems				
120mm M256	M1A2 Main Battle Tank	WVA	GD	Chamber & Bore
155mm M284	M109A6 SP Howitzer	WVA	BAE, NA	Chamber, Split & Inner Rings, Spindle
155mm M199	M198 Towed Howitzer	WVA	RIA	Chamber, Split & Inner Rings, Spindle
105mm M20	M119 Towed Howitzer	WVA	RIA	Chamber, Split & Inner Rings, Spindle
120mm M298	M120 Towed / M121 (1064 APC)	WVA	PM-Mortars	Elevation-Traverse Mechs
81mm M29A1	M29A1 / M125 APC	WVA	PM-Mortars	Elevation-Traverse Mechs
81mm M253	M252 Ext. Range Mortar	WVA	PM-Mortars	Elevation-Traverse Mechs / Bi-Pod
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Systems Under Development				
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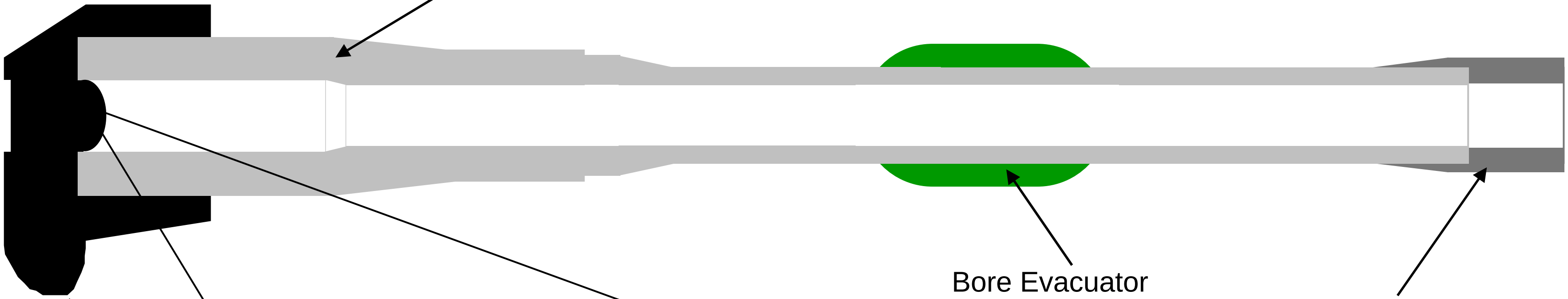
120mm XM325	NLOS-M	TBD	TBD	TBD
155mm M776	M777 Towed Howitzer	WVA	BAE, UK	Chamber, Split & Inner Rings, Spindle

Chrome Plating also used at WVA for repair/build-up of damaged/out-of-spec large caliber cannon components

Cadmium is not used in Army Large Caliber Cannon Assemblies

Large Caliber Cannon Assembly

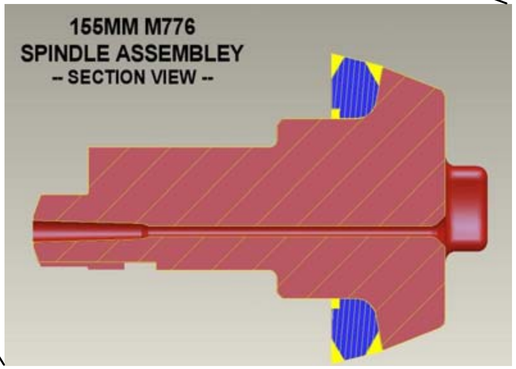


Barrel

Bore Evacuator
(Howitzer Cannon only)

Muzzle Brakes
(All Howitzer Cannon
& Future guns)

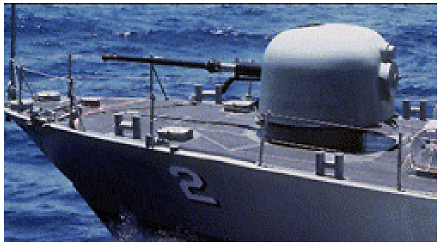
Breech Ring Assembly
- Breech Ring
- Breech Block
- Spindle Assy, etc



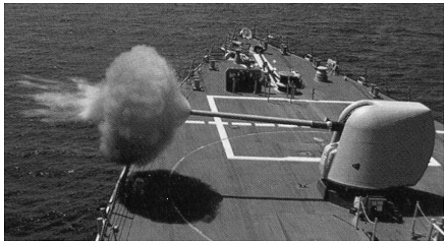
Cannon Nomenclature
- **Howitzers (indirect fire)**
- **Guns (direct fire)**
- **Mortars (indirect fire)**

NAVY LARGE CALIBER ARMAMENT SYSTEMS

Gun Type	Weapon System	Gun Mfr’er	Cr-Plating
Fielded Systems			
76mm Mk75	Perry-Class Frigate	BAE, NA	Mk33 Liner Chamber & Bore
5” Mk45 (54 cal)	Ticonderoga, Burke, Spruance-class ships	BAE, NA	Chamber & Bore
5” Mk45 Mod4 (62 cal)	Ticonderoga, Burke-class ships	BAE, NA	Chamber & Bore
Systems Under Development			
155mm AGS	DD-X Destroyer	BAE, NA	Not Gun Bore, other areas ??



76mm Mk75 Gun



5” Mk45 Gun

155mm AGS

Tri-SERVICE MEDIUM CALIBER ARMAMENT SYSTEMS

CALIBER (mm)	GUN BARREL	ARMAMENT SYSTEM	WEAPON SYSTEM	WEAPON SYSTEM NAME
20mm	GAU-4	Vulcan	F/A-18, F-15, F-16, F-22A, F-14A/B/D	Hornet, Eagle, Falcon, Raptor, Tomcat Fighting Aircraft
		3-Barrel Gatling Gun	AH-1W	Super Cobra Helicopter
20 mm	M61A1	Mk15, Phalanx CIWS	Kitty Hawk, Nimitz, Ticonderoga, Spruance, Burke, Perry, Wasp, Tarawa-class ships	Carriers, Cruisers, Destroyers, Frigates, Landing and Amph. Assault Ships
20 mm	XM-301	3-Barrel Gatling Gun	RAH-66	Comanche Helicopter
25 mm	GAU-12		F-35, AV-8B, AC-130H/U	Joint Strike Fighter, Harrier, Gunship
25 mm	M242	Bushmaster	M2/M3, LAV-25, Ticonderoga, Perry, Cyclone, & San Antonio-class ships	Bradley FV, LAV, Cruiser, Frigate, Coastal Patrol, Docking Ship
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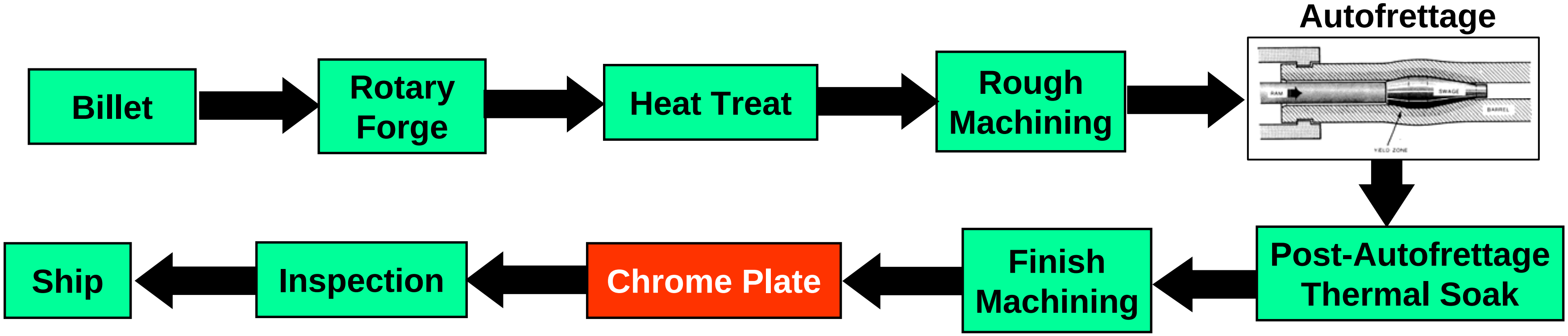
30 mm	M230	Chain Gun	AH-64	Apache Helicopter
30 mm	Mk44	Bushmaster II	EFV, LPD-17, MH-53E. AC130	Amph Assault Vehicle, Amph. Ship, Helicopter, Gunship

- **Approx. 40,000 units will be produced between 2004-2013**
- **Production of medium caliber guns resides in the private sector (GD, ATK, etc)**

ARMY 120mm GUN BARREL MANUFACTURING PROCESS


Billet → Rotary Forge → Heat Treat → Rough Machining → Autofrettage → Post-Autofrettage Thermal Soak → Finish Machining → Chrome Plate → Inspection → Ship


Rotary Forging

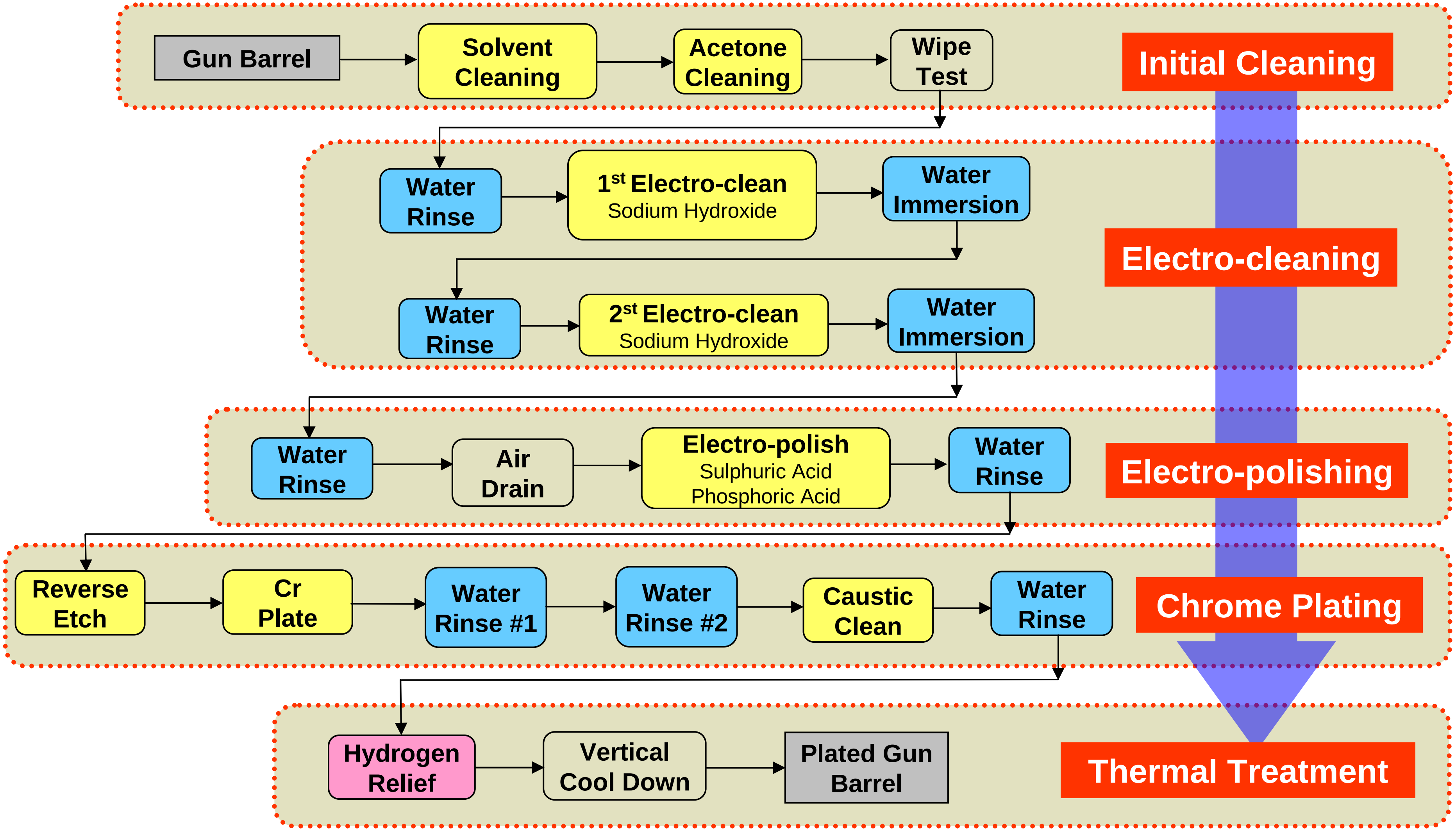

Machining


Chrome Plating

Fielding

PRODUCTION CHROME PLATING

Large Caliber Gun Barrels



Initial Cleaning

Gun Barrel → Solvent Cleaning → Acetone Cleaning → Wipe Test

Electro-cleaning

Water Rinse → 1st Electro-clean Sodium Hydroxide → Water Immersion

Water Rinse → 2st Electro-clean Sodium Hydroxide → Water Immersion

Electro-polishing

Water Rinse → Air Drain → Electro-polish Sulphuric Acid Phosphoric Acid → Water Rinse

Chrome Plating

Reverse Etch → Cr Plate → Water Rinse #1 → Water Rinse #2 → Caustic Clean → Water Rinse

Thermal Treatment

Hydrogen Relief → Vertical Cool Down → Plated Gun Barrel

NEW PEL REQUIREMENTS

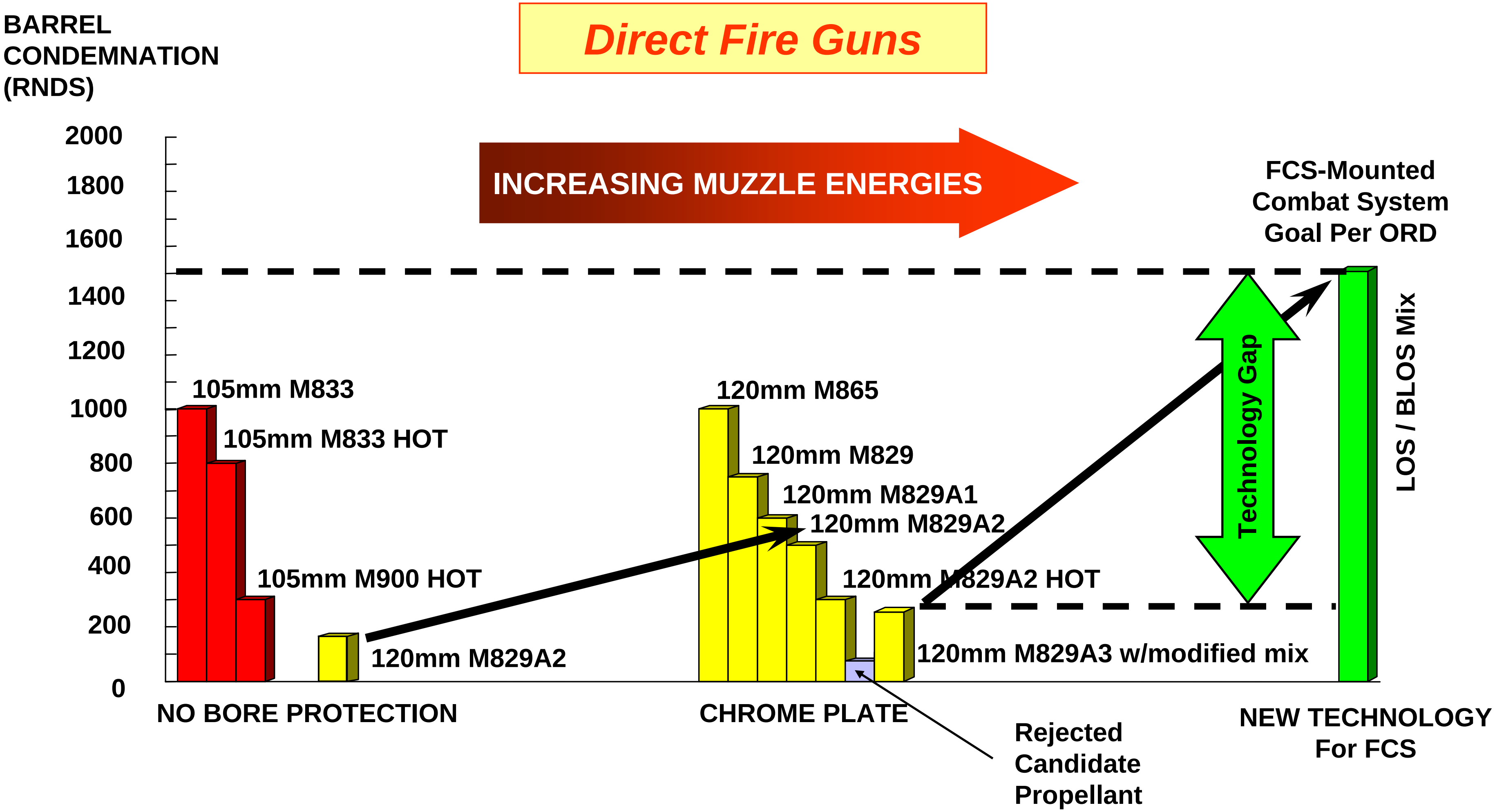
- The new standard lowers OSHA's permissible exposure limit (PEL) for hexavalent chromium, and for all Cr(VI) compounds, from 52 to 5 micrograms of Cr(VI) per cubic meter of air as an 8-hour time- weighted average.

- Hexavalent chromium compounds are widely used in the chemical industry as ingredients and catalysts in pigments, metal plating and chemical synthesis. Cr(VI) can also be produced when welding on stainless steel or Cr(VI)-painted surfaces.

- Major health effects associated with exposure to Cr(VI) include:
  - lung cancer
  - nasal septum ulcerations and perforations
  - skin ulcerations
  - allergic and irritant contact dermatitis

From 52 to 5 micrograms of Cr(VI) per cubic meter of air as an 8-hour time- weighted average

WHY LARGE CALIBER GUNS USE CHROME PLATING

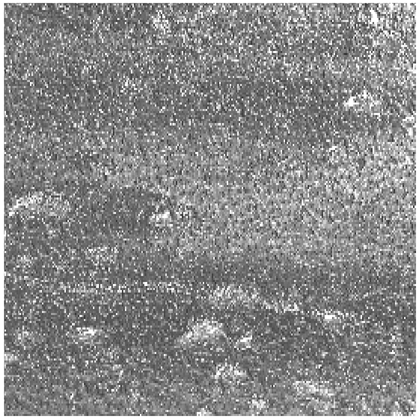


“Provide Innovative Armaments Solutions for Today and Tomorrow”

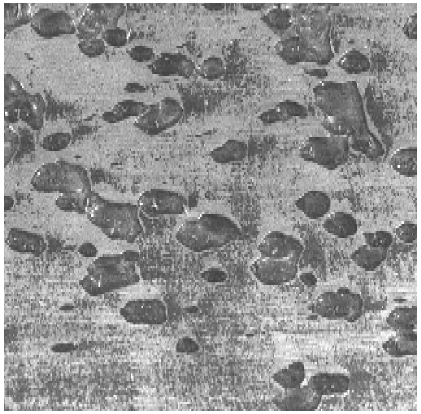
ARDEC

GUN BARREL DEGRADATION

Classic Erosion Defined

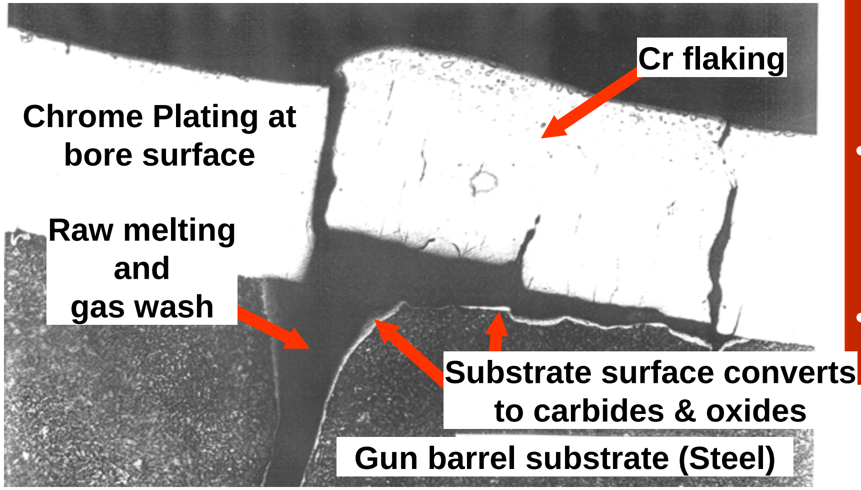


101 M829 rounds
771 Total rounds



39 Rejected candidate M829E3
214 Total rounds

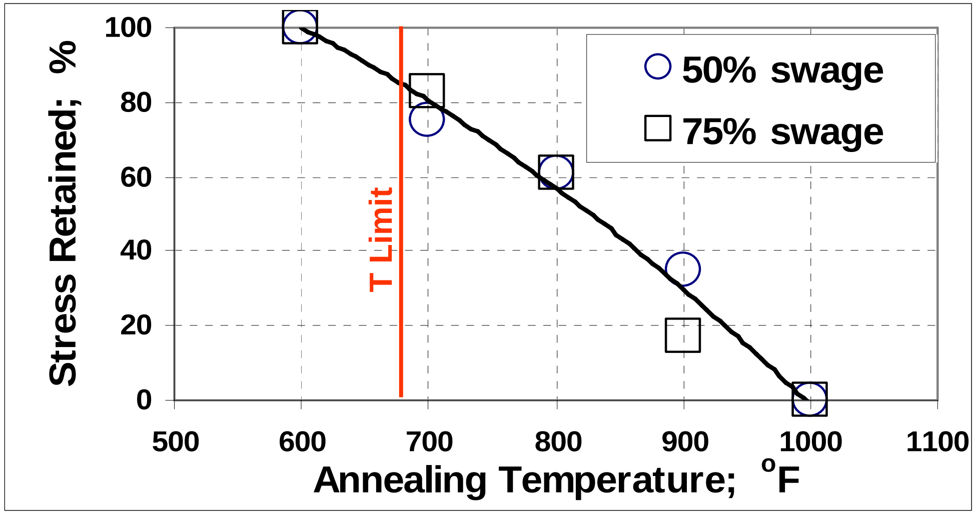
ABRAMS 120mm GUN BARREL



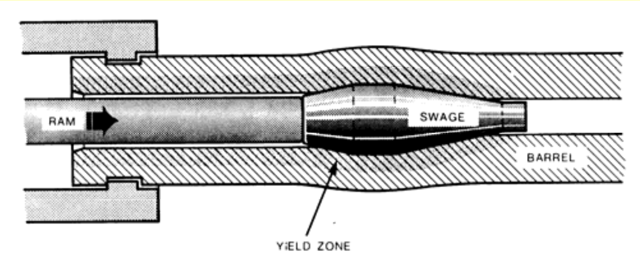
- HC Chrome is produced in an "as cracked" condition offering path to substrate
- HC Cr contaminants off-gas causing further material volume shrinkage and stress-relief cracking
- Combustion products:
  - Penetrate cracks
  - Alter steel substrate phase
  - Convert substrate surface to carbides & oxides
  - Lowers MP of substrate surface
- Gas wash:
  - Removes lower MP substrate surface
  - Erodes Cr foundation (compromised adherence)
- Departing Cr exposes more substrate to high velocity gas wash and further erosion

LARGE CALIBER GUN BARREL STRENGTH

Coating Process Temperature Limitations



Residual stress retained following 2 hr furnace heating of 120mm M256 gun barrels



Swage Autofrettage

Yield Strength, Static and Dynamic, ksi

M256

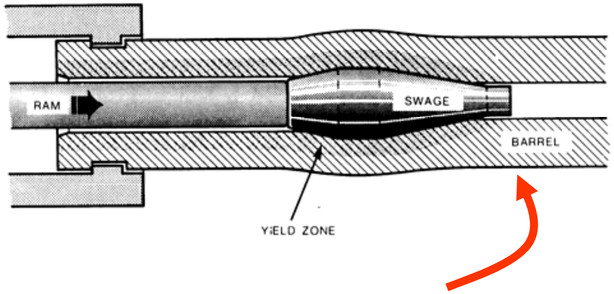
		1120 static 1220 dynamic		**1200 static 1300 dynamic**		**1300 static 1400 dynamic**	
Temp, F	**% Ret.**	**Cycles**	**Bore Stress**	**Cycles**	**Bore Stress**	**Cycles**	**Bore Stress**
600	**100**	4960	1190	6110	1070	7870	940
700	**81**	4120	1310	4970	1190	6220	1060
800	**57**	3320	1470	3930	1340	4790	1210
900	**31**	2680	1640	3110	1520	3710	1380
1000	**0**	--	--	--	--	--	--

Autofrettage allows gun barrels to be lighter and stronger

GUN BARREL COATING REQUIREMENTS

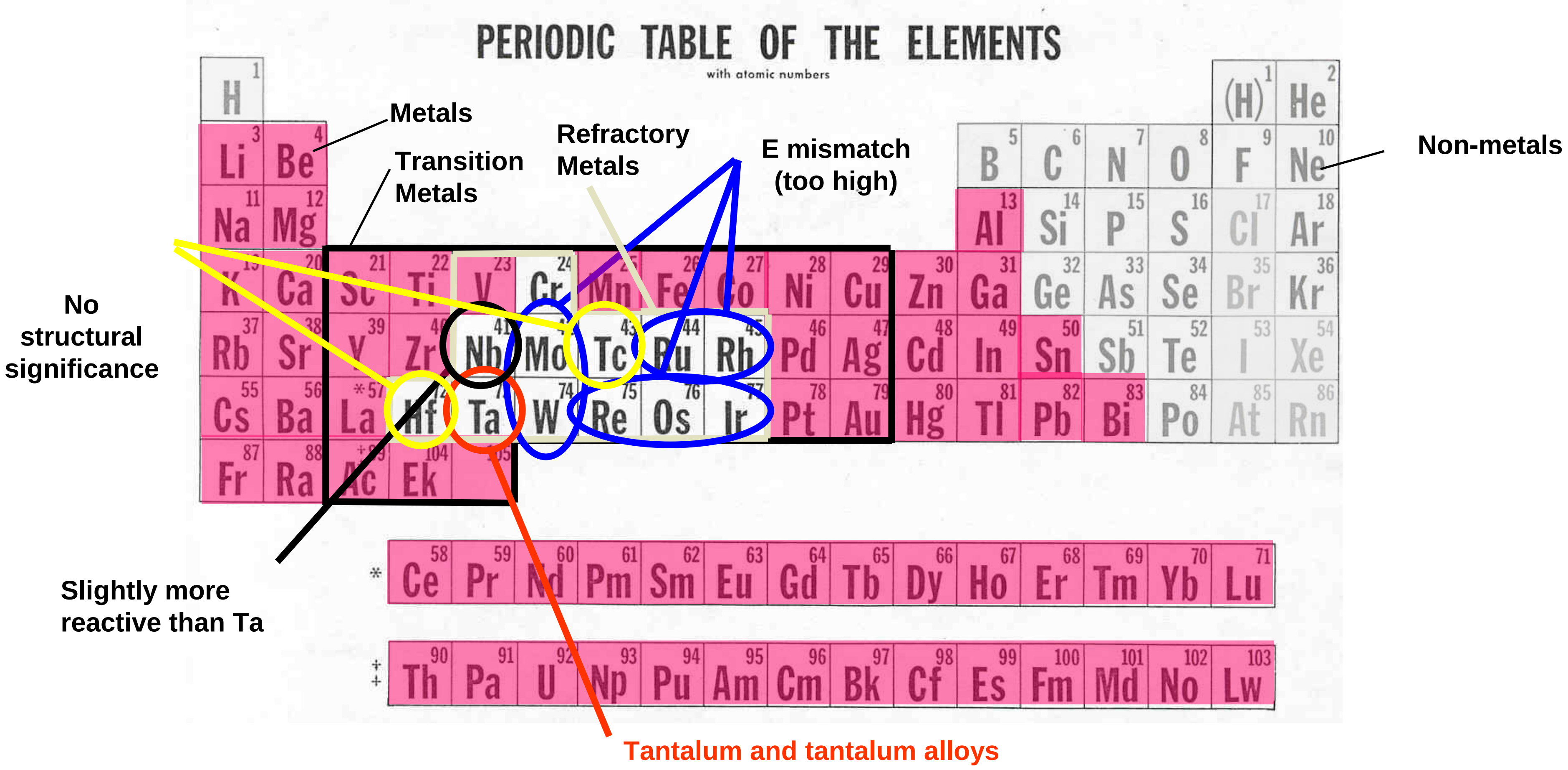
Material & Deposition Process Requirements

MATERIAL CHARACTERISTIC	CRITERIA
Melting Point	*Cr (1875 C) or better*
Elastic Modulus	*Compatible with substrate* ***(facilitates low surface crack densities)***
YS at Elevated Temps	*High*
Fracture Toughness	*High*
Hot Hardness	*High (appropriate)*
Chemical Resistance	*High*
Coefficient of Thermal Exp.	*Compatible with substrate*
Thermal Conductivity	*Low*
Reaction w/ Rotating Band	*Inert*
Phase Transformations	*None*



PROCESS CHARACTERISTIC	CRITERIA
Deposition Temperature	*Less than 357C* ***(post autofrettage thermal soak limit – Lg Cal ONLY)***
Deposit Rate	*1 mil of coating material per hour*
Surface Finish	*Equal or better than 32 RMS at deposition*
Deposition Length	*58 Calibers or greater (Lg Cal ONLY)*
Hazardous Impacts	*None or limited*

REPLACEMENT COATING MATERIAL SELECTION



Metals

Transition Metals

Refractory Metals

E mismatch (too high)

Non-metals

No structural significance

Slightly more reactive than Ta

Tantalum and tantalum alloys

Rh, Ru, Tc, Hf, Nb, Mo, Ta, W, Re, Os, & Ir exceed MP of Cr

DEPOSITION PROCESS SELECTION

for Large Caliber Guns

	PROCESSES						
MAJOR FUNCTIONAL REQUIREMENTS	**Electro-deposition via Molten Salts**	**Plasma Spray**	**CVD**	**Ion-based Processes**	**Explosive Bonding**	**Electroplated Chrome**	**Magnetron Sputtering**
Autofrettage Stresses Protected (Lg Cal ONLY)				X		X	X
No Post-process Surface Finish Req	X			X		X	X
Acceptable Deposition Rate	X	X	X		X	X	X
Proper Process Aspect Ratio			X			X	X
Accept Dim. and Densities over 50 cal (Lg Cal Only)						X	X
Acceptable Adhesion	X				X	X	TBD
Accommodates Rifled Barrels	X		X			X	
Dry Process		X	X	X	X		X
Eliminate Hazardous Materials		X		X	TBD		X
Eliminate Air / Water Contamination				X	TBD		X

MAJOR EXISTING PROGRAMS

Chromium Replacement in Cannon

The Army and the Navy are both focusing their Chrome Replacement/Life Extension programs for guns on:

Magnetron Sputtering
Explosive Cladding

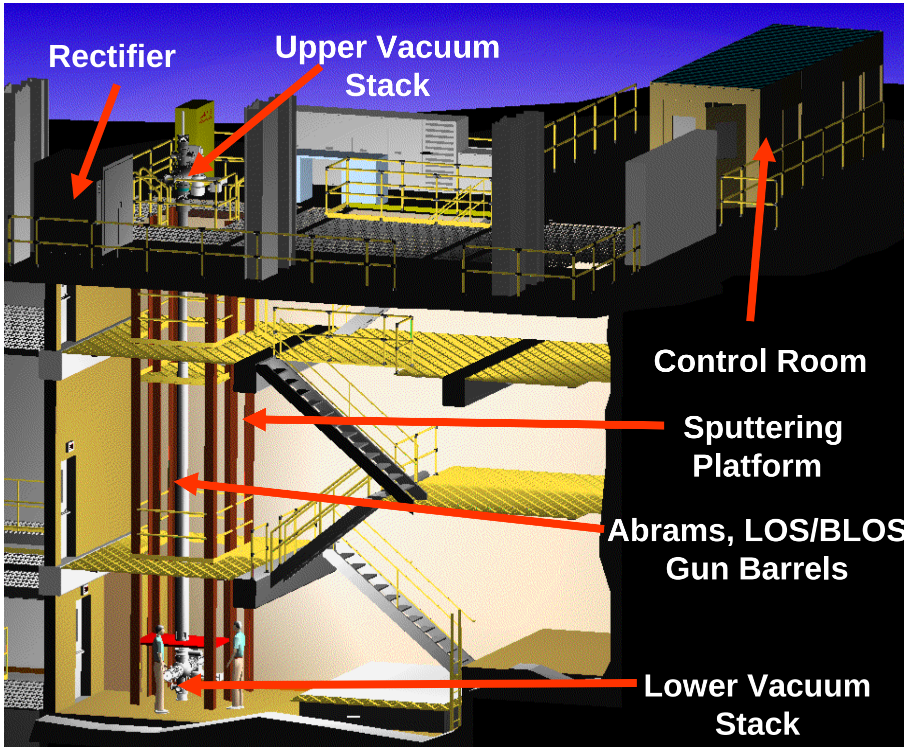
- **Army Programs**
  - **ManTech #00-01: Cannon Life Extension via Magnetron Sputtering Technology (120mm)**
  - **SERDP #1426: Chromium Replacement in Medium Caliber Guns (25mm)**

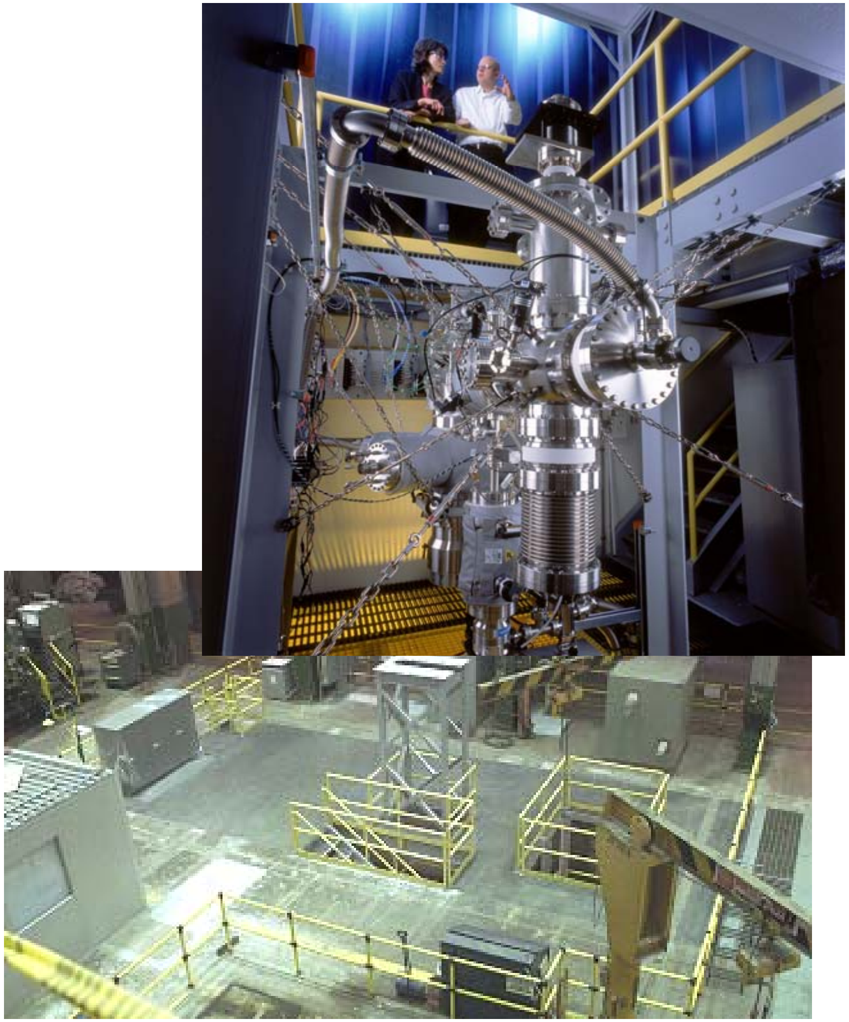
- **Navy Programs**
  - **Future Naval Capabilities Program: Advanced Gun System (AGS) (155mm)**

Program	System	FY05	FY06	FY07
ManTech #00-01	Lg Cal-direct fire	$1.60M	$3.00M	$1.00M
SERDP #1426	Med Cal	$0.65M	$0.70M	$0.55M
Navy AGS	Lg Cal-indirect fire	???	???	???

LARGE CALIBER CHROME REPLACEMENT

Magnetron Sputtering (Army)





Coupons

Full-Dia. Liners

Full-sized Barrels

STATUS OF TECHNICAL METRICS

Magnetron Sputtering (Army)

CHARACTERISTIC	HC CHROME PLATING	Goal for SPUTTERING	VERIFICATION TECHNIQUE	CURRENT STATUS
Coating Morphology	Zone 2	Zone 2	Microscopy	yes
Coating Phase	Single	100% Alpha (Ta)	Microscopy	yes
		bcc (Cr)	Microscopy	yes
Hardness	1100 Knoop	300 Knoop	Microhardness	yes
Thermal Shock Resistance	Poor	Excellent	Pulsed Laser	yes
			Vent. Eros. Sim(VES)	yes
Adhesion / Cohesion	Excellent	Excellent	Groove Testing	yes
			VES (Ta)	yes
			Firing Tests	no
Distribution over Length	.002 - .006 in.	Less than .0005	Microscopy	yes (80”)
Distribution around ID	.002 - .006 in.	Less than .0005	Microscopy	yes
Deposition Rate	.001 inches/hr	.001 inches/hr	Microscopy	no (.00075)
Coating Thickness	.002 - .006 in.	.004 - .006 in.	Microscopy	yes
Surface Finish	63 finish	32 or better	Visual	yes (16)
Onset of Erosion	100 VES shots	better	Visual / Microscopy	yes
Weapon Service Erosion Life	260 Rnds (M829A3)	equiv (Envir)/400 (Perf.)	Firing Tests	in-process

Last Firing Test – Liner 3A: 100 M829 Rounds, still serviceable (Process Rev Date: Apr 05)
Next Firing Test – Liner 4B: Jun 06, numerous process improvements (Process Rev Date: Mar 06)

REMAINING CHALLENGES

Magnetron Sputtering (Army)

CHALLENGE	**TECHNICAL APPROACH**
ADHESION	* Improved vacuum system including improved out-gassing (bakeout) practice * Pursuing ion bombardment (e.g. pulsed CMS, A/C) to remove interface impurities * Exploiting thin film testing for rapid turnaround and adhesion optimization * Improving plasma cleaning of target/substrate prior to deposition * Investigate precision cleaning (e.g. DI water rinse, flash rust inhibitors, CO2 snow) * Plasma cleaning with modified plasma cleaning device (PCD) shields * Modified PCD to deposit CMS Cr seed layer * Bias sputtering to deposit Ta directly on steel or biased interlayer * Proper preservation of barrel test sections after WVA pre-processing steps before insertion into CMS platform (e.g. cap with positive Ar pressure)

120mm Gun Liner 1 (2005)

- 61 Rounds (condemned)
- Lost 60% of coating
- Mix of Alpha/Beta Ta
- Low Adhesive Strength

120mm Gun Liner 3 (2005)

- 99 Rounds (not condemned)
- Lost 15% of Coating
- All Beta Ta
- Better Adhesive Strength

120mm Gun Liner 4B (2006)

- Firing in June
- All Alpha Ta
- Much Higher Adhesive Strength
- Best In-House VES testing to-date

Progress has been slower than desired but progress is being made….need to maintain funding through completion

FUTURE INVESTMENT AREAS

Magnetron Sputtering

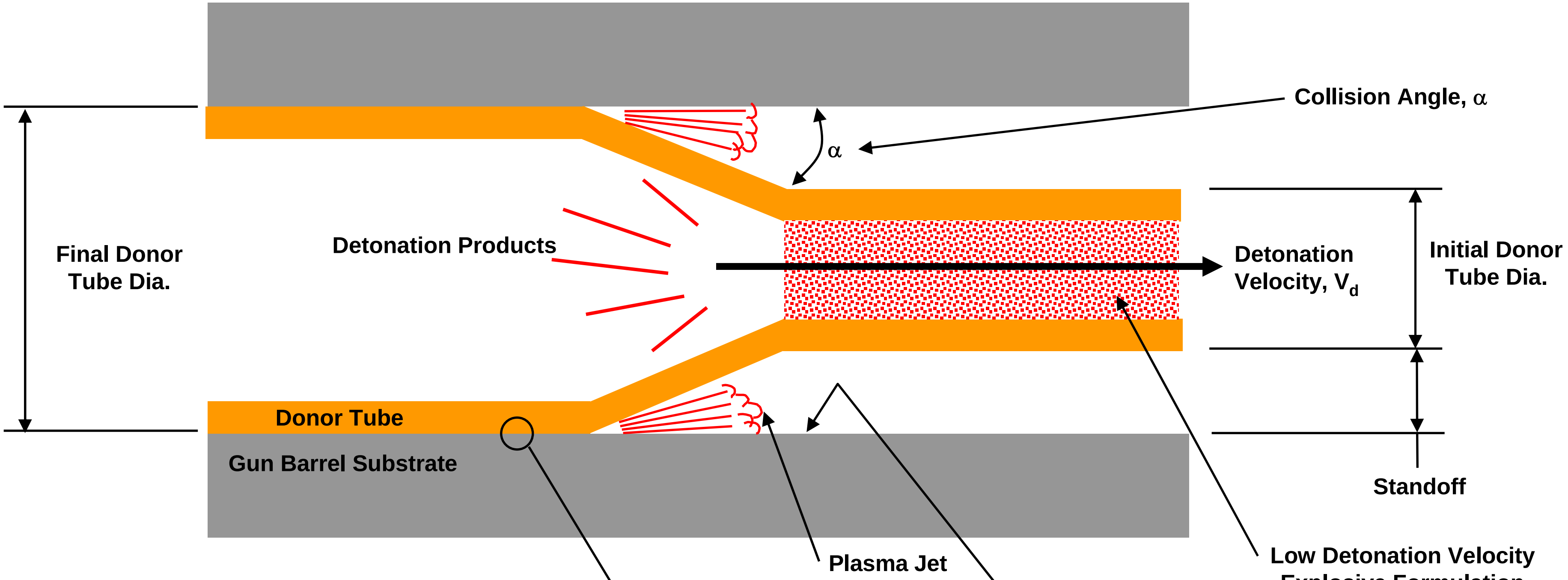
Focus Area: Evaluation of a cold cathode on CMS performance
Justification: Currently use a hot cathode for CMS which is atypical in industry. Use of a cold cathode will increase deposition rate, reduce coatings contamination, and facilitate scale-up of CMS technology.
Cost: $500K (R.O.M. est.)

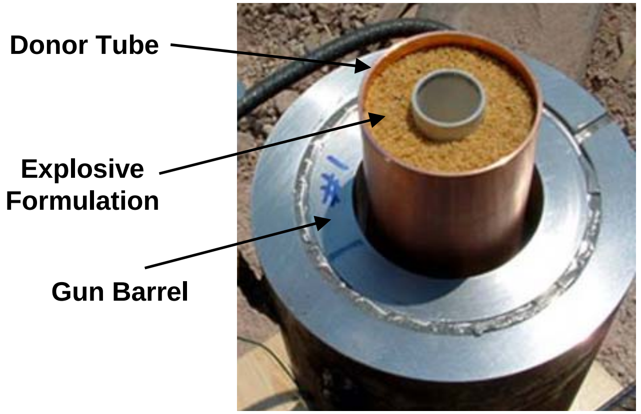
Focus Area: Post Processing of CMS coatings to improve adhesion
Justification: To provide local heating to promote diffusion bonding and improved adhesion
Cost: $500-1000K (R.O.M. est.)

Focus Area: Reactive chemical cleaning
Justification: To utilize low voltage hydrogen plasma chemical cleaning to mitigate issues with recontamination of material from current plasma cleaning technique, to improve adhesion, and to facilitate scale up of CMS process.
Cost: $300K (R.O.M. est.)

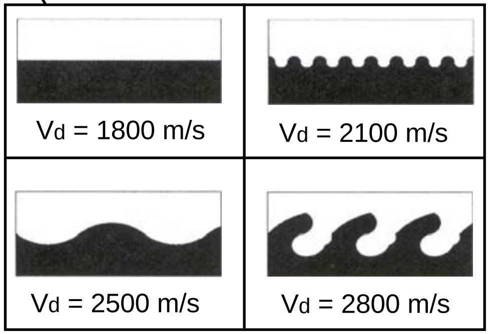
MEDIUM CALIBER CHROME REPLACEMENT

Explosive Cladding (Army)





Bond Interface



Plasma Jet Scrubs Surface in Advance of Donor Tube

EXPLOSIVE CLADDING

Prior Work – SBIR Phase I & II

SBIR Objectives:

(1) Test the Erosion Resistance of Tantalum with Most Erosive Ammunition Available (XM919)
(2) Demonstrate Bond Strength of Cladded Bore Liners by Firing to Destruction

- **Utilized Scrap Bushmaster Barrels**
- **Smoothbore Design: Focus on Erosion Resistance and Bond Strength**
- **No-Twist Rifled Design: Assure Proper Sabot Confinement/Functionality for M919 ammo**

- **XM919 (APFSDS-T) Lot No. ADJ91D365-002**
  - **Original formulation that condemned Bushmaster barrel in 229 rounds (1991)**
- **HES9053 Propellant - Flame Temp of 3692 K**
- **Cycle B Firing Schedule, 150 rounds/Cycle IAW TECOM 1-WE-100-BUS-050**

Tested March 26-31, 2001 at ATC

- **Smoothbore Design**
  - **Fired 1385 rounds**
  - **No significant increase in dispersion**
  - **Barrel still considered serviceable**

- **Rifled Design**
  - **Fired 600 rounds**
  - **No significant increase in dispersion**
  - **Barrel still considered serviceable**
  - **Did not exceed condemnation limit of the BG10 barrel bore gage after 600 rounds**
  - **Exhausted ammunition supply**

- **Baseline Barrel**
  - **Nitrided Bushmaster barrel**
  - **Condemned after 229 rounds**

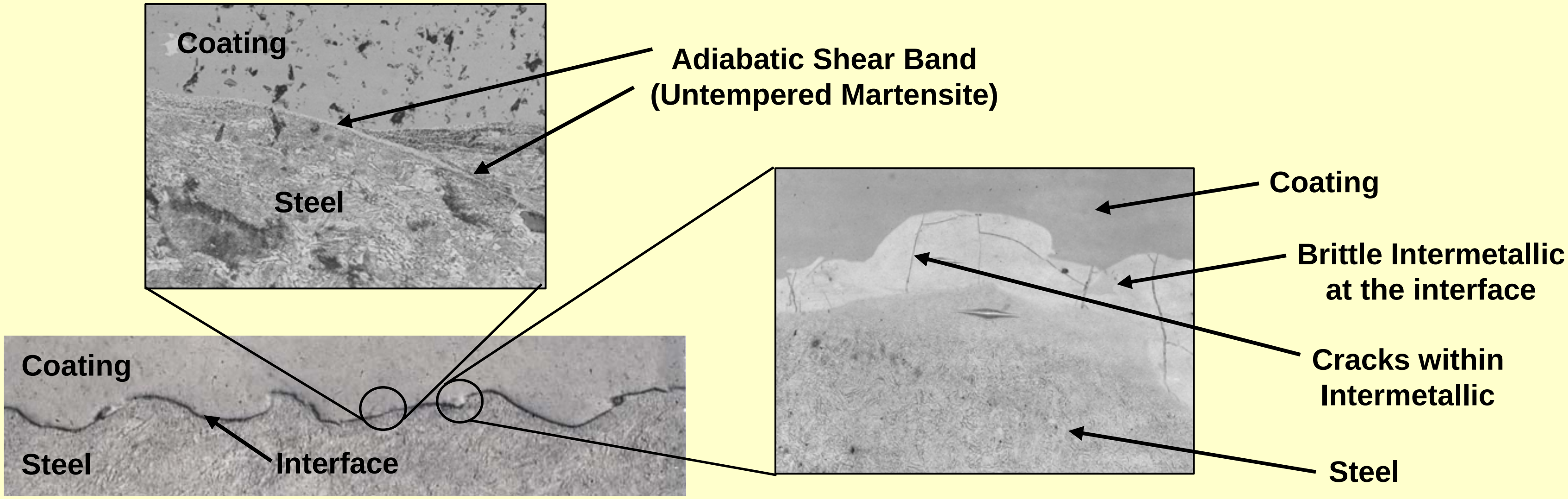
EXPLOSIVE CLADDING

Remaining Challenges

- **Increased hardness for rifling applications**
- **Reduce / eliminate Adiabatic Shear**
- **Reduce / eliminate Intermetallics**
- **Manage interface characteristics**
- **Wear Life**

Rifling Before Firing

Rifling After Firing



LARGE CALIBER CHROME REPLACEMENT

Magnetron Sputtering (Navy)

45mm UDLP (now BAE) Demonstrator

FY04

USN 76mm Mk 75 Gun Demonstrator

FY06

155mm FNC-AGS

FY09

76mm Down-Selection Test – Jun 06

Magnetron Sputtering vs. Explosive Cladding

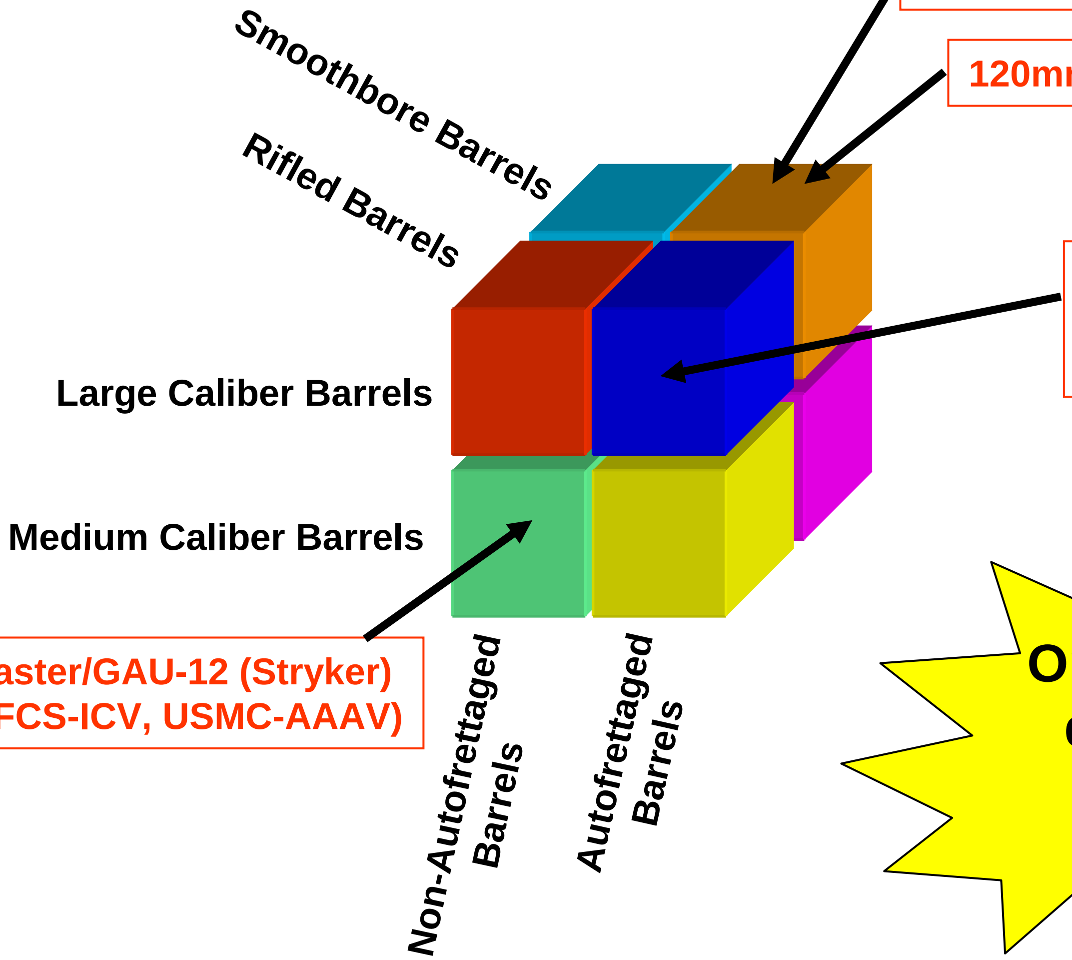
ARMY STAKEHOLDERS FOR Cr ELIMINATION IN GUN BARRELS

- PM-FCS
- PM-Lethality
- PEO-Ammo
- Army EQT

The most important stakeholder of these Cr-elimination technologies is the production employees responsible for applying coatings to gun barrels

CANNON BARREL TECHNOLOGY

System Application Graphic



Smoothbore Barrels

Rifled Barrels

Large Caliber Barrels

Medium Caliber Barrels

Non-Autofrettaged Barrels

Autofrettaged Barrels

120mm M256 Abrams

120mm FCS-MCS

155mm FCS-NLOS-C
USN 155mm AGS
155mm XM777 Howitzer

25mm Bushmaster/GAU-12 (Stryker)
30mm Mk 44 (FCS-ICV, USMC-AAAV)

One “shoe” does not fit all !

CONSIDERATIONS FOR PROCESS SELECTION

		Pros	Cons
Caliber	**Large Caliber**	More room for process equipment	Usually autofrettaged, cannot accommodate process temps >315C
	Medium Caliber	Can accommodate higher process temps	Limited room for certain processes and equipment
Residual Stress Level	**Autofrettaged**		Cannot accommodate process temps >315C
	Non-Autofrettaged	Can accommodate higher process temps	
Bore Configuration	**Rifled**		Cannot accommodate Line-of-Sight processes, greater engraving force requirements, dimensional uniformity a challenge
	Smoothbore	Little process limitations, no engraving force requirements, easier dimensional uniformity	

SUMMARY

- **The primary and most widely-used bore protection technology currently used for DoD large and medium caliber guns is chromium plating**
  - 20 (+/-) fielded and proposed gun designs, mounted on 40 (+/-) weapons platforms use chrome plating as bore protection
  - On average, between 2,000 and 4,000 Cr-plated gun barrels are produced each year by DoD

- **Both the Army and the Navy have separately down-selected to Magnetron Sputtering and Explosive Cladding coating technologies**
  - Army Lg Cal - Sputtering, Med Cal - Cladding
  - Navy Lg Cal - Both Sputtering and Cladding

- **Funding needs to continue to push technologies over final hurdles**

- **Implementation of these technologies will completely eliminate the need for Cr-plating of gun barrels**