

Replacing hard Cr and Cd - choosing the best options

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RUST 2001

Sources of information

- ❑ **Information from various programs**
 - **HCAT chrome replacement**
 - **JSF - technology analysis of Cr and Cd replacement options, including ID and field repair**
 - ❑ **development of semi-quantitative evaluation techniques**
 - **SERDP programs on ID chrome replacement**
 - **SERDP program on development of stainless landing gear steel - evaluation of environmental and cost impacts**
 - **New materials development in Canada - various companies and NRC**

Environmental concern is
a driver for change

but when the chips are down

acceptance is driven by
cost
performance
reliability



Cr and Cd applications

❑ Hard chrome (wear resistance)

- Landing gear
- Hydraulics
- Gun tubes
- Rebuild of worn items
- ODs and IDs



❑ Cadmium (corrosion resistance)

- Components
- Fasteners
- Electrical connectors



Replacement options

❑ Hard chrome

- **Electro- and electroless Ni and composites (ODs and IDs)**
- **Thermal sprays**
 - ❑ HVOF (ODs)
 - ❑ plasma spray (ODs, IDs)
- **Welding**
 - ❑ arc, laser welding
 - ❑ explosive bonding
 - ❑ electrospark alloying
- **PVD sputtering (Green gun barrel IDs)**

❑ Cadmium

- **Aqueous electroplates**
 - ❑ Zn-Ni, Sn-Zn
- **Non-aqueous electroplates**
 - ❑ molten salt Al-Mn
 - ❑ organic solution Al (Alumiplate)
- **PVD vacuum Al**
 - ❑ IVD Al
 - ❑ sputtered Al for IDs
- **SemeTels (ceramic-metal)**
- **Metal-filled polymers**
- **New designer stainless**

Note: almost everything must be chromated

Each of these has different capabilities and applications
Likely to be only 2 or 3 winners, with various niche products

Metrics for deciding on options

Decision metrics - the Technology Assessment Matrix

- ❑ **Technology Assessment Matrix method developed for Joint Strike Fighter program**
 - **What technology alternatives are out there?**
 - **What will make technical and logistical sense?**
 - **Which options are close enough to production either**
 - ❑ **for OEM use?**
 - ❑ **for MRO use a few years down the road?**
 - **What are the **critical gaps****
 - ❑ **What time, money, resources will it take to bring to production?**
- ❑ **Method can be applied to any technology, material, etc., - even software**
- ❑ **Purpose is to replace hand-waving and intuition with quantitative logic**

Choosing the best option for the application

- Technology Assessment Matrix

What are the engineering and fit requirements?

How well does the new process meet these requirements?

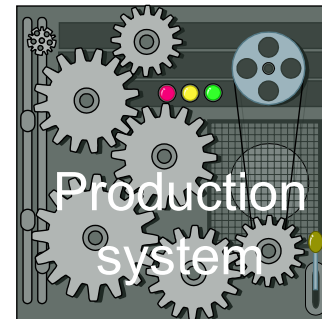
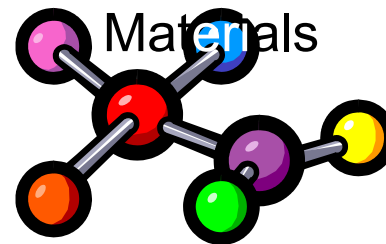
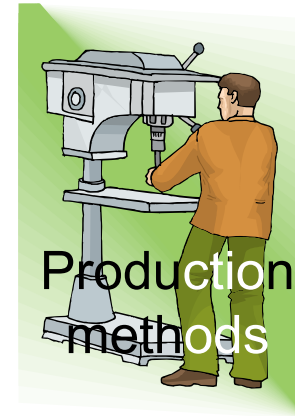
What are the production steps in the new process?

How well developed is each production step?

Where are the gaps?

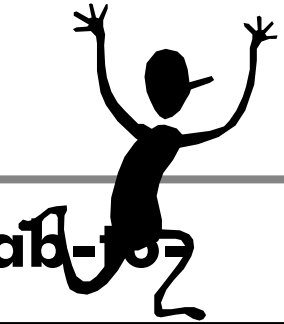
What are the costs to production?

Technology Assessment Matrix - Assessing a new technology

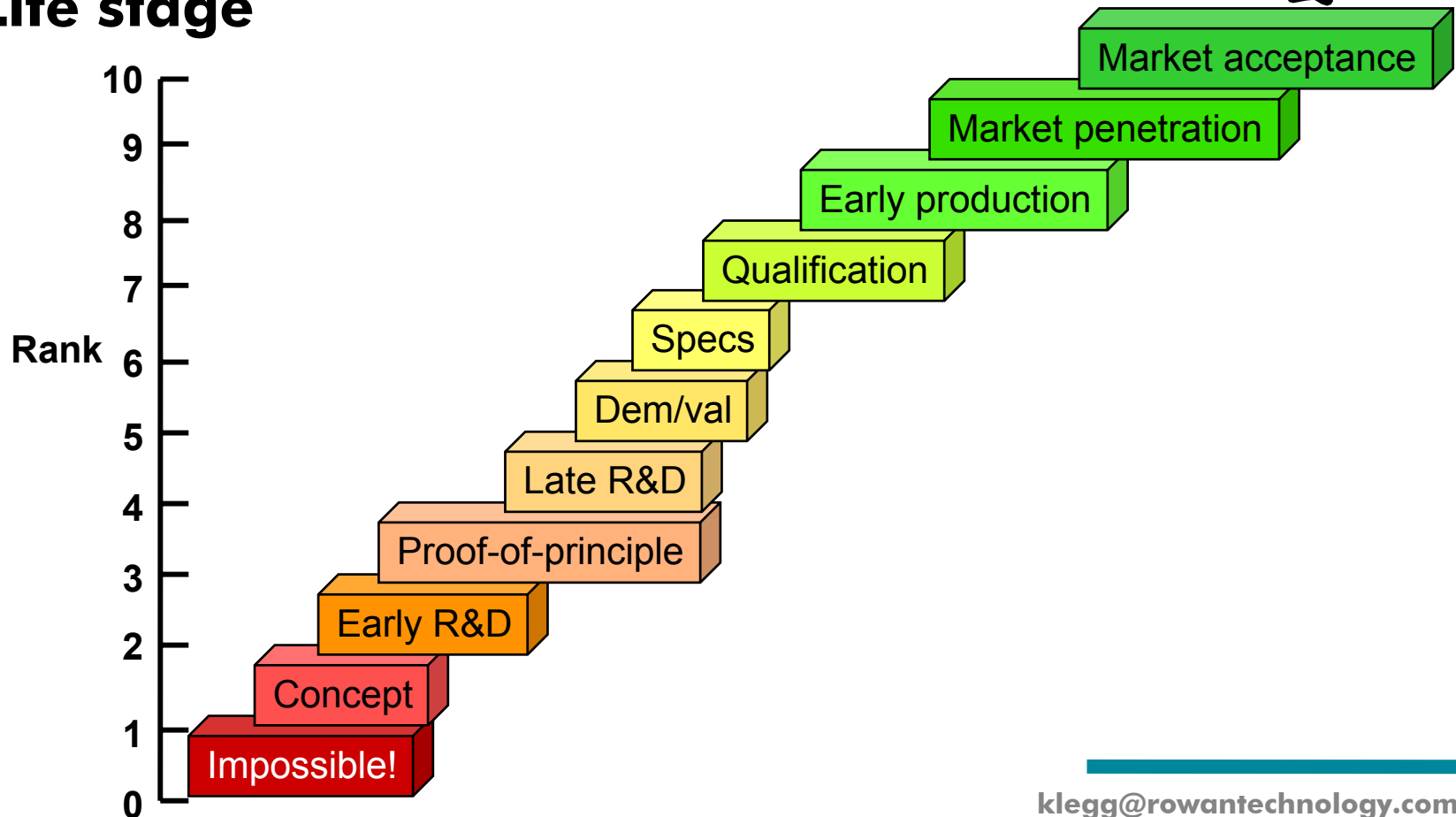


- ❑ What is critical to each process step?
- ❑ How advanced is the technology for each step?

Technology Assessment Matrix - Semi-objective criteria



- Objective milestones used to decide on Lab-to-
Life stage



General coating requirements

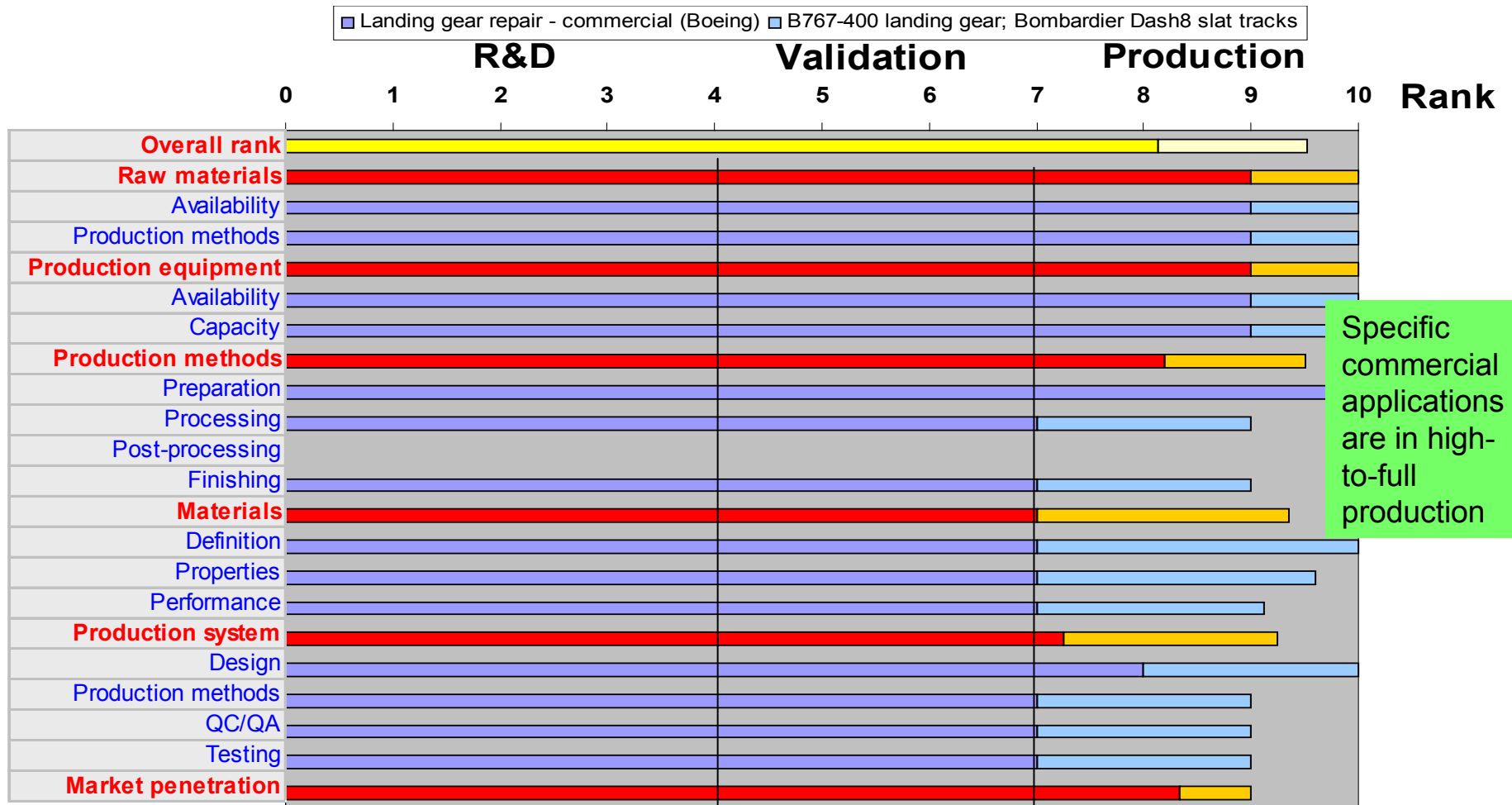
Chrome

- ❑ **Thickness - 0.0003 (thin dense Cr) to 0.015 (rebuild)**
- ❑ **Hardness (600 - 1,000 HV), wear/corrosion resistance**
- ❑ **Porosity <2% to prevent gas/fluid leakage**
- ❑ **Low fatigue debit**
- ❑ **Low embrittlement**
- ❑ **Capable of fine finish (minimize seal wear)**
- ❑ **Good process control**
- ❑ **Fit with OEMs, depot and field repair**

Cadmium

- ❑ **Thin (<0.001"), smooth (no refinishing)**
- ❑ **Corrosion resistance B117 2,000 hrs**
- ❑ **Low fatigue**
- ❑ **Low embrittlement**
- ❑ **Proper torque (fasteners)**
- ❑ **Low impedance (connectors)**
- ❑ **Good process control**
- ❑ **Fit with OEMs, depot and field repair**

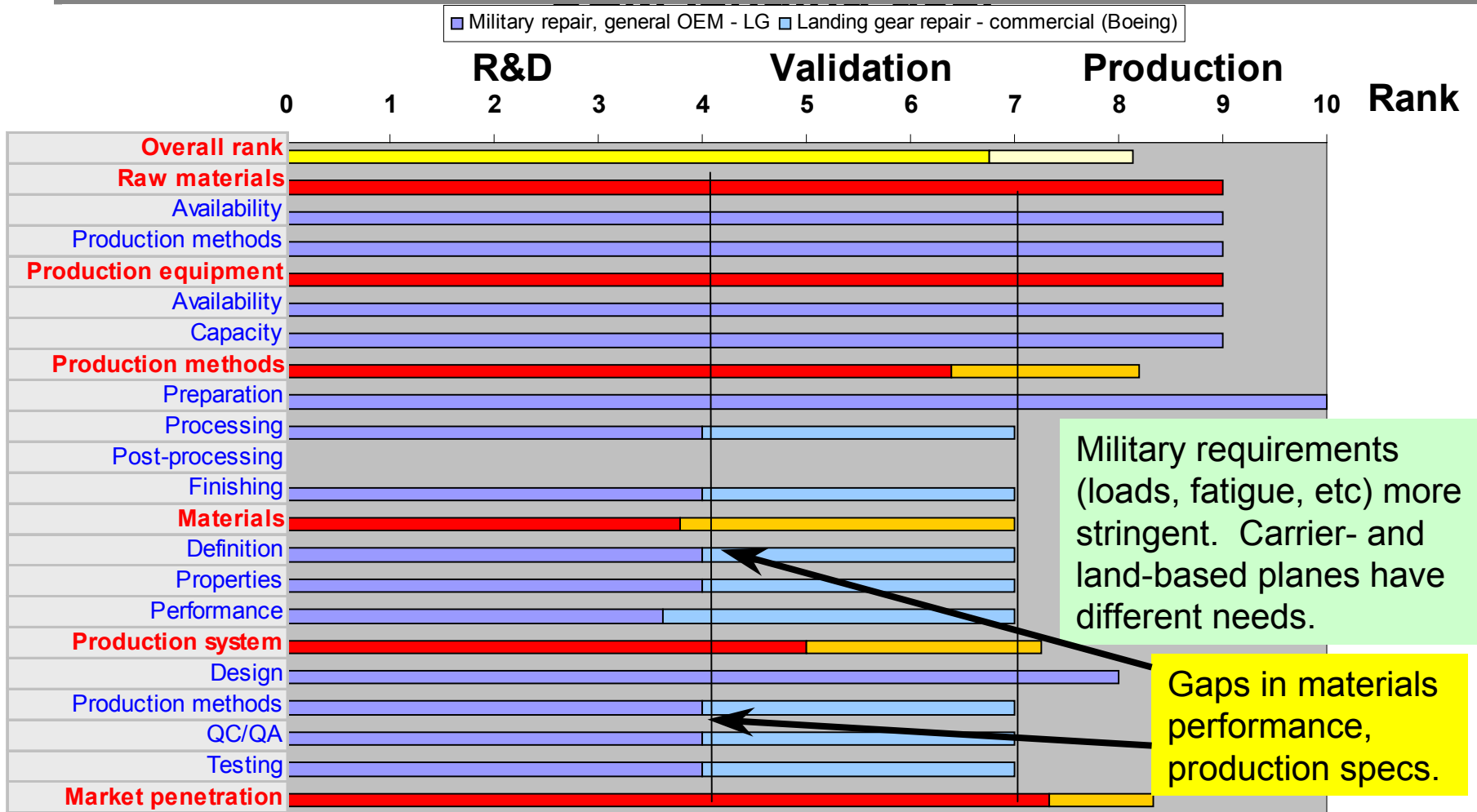
HVOF for chrome replacement on aircraft ODs - commercial repair



Specific commercial applications are in high-to-full production

General commercial replacement currently small scale

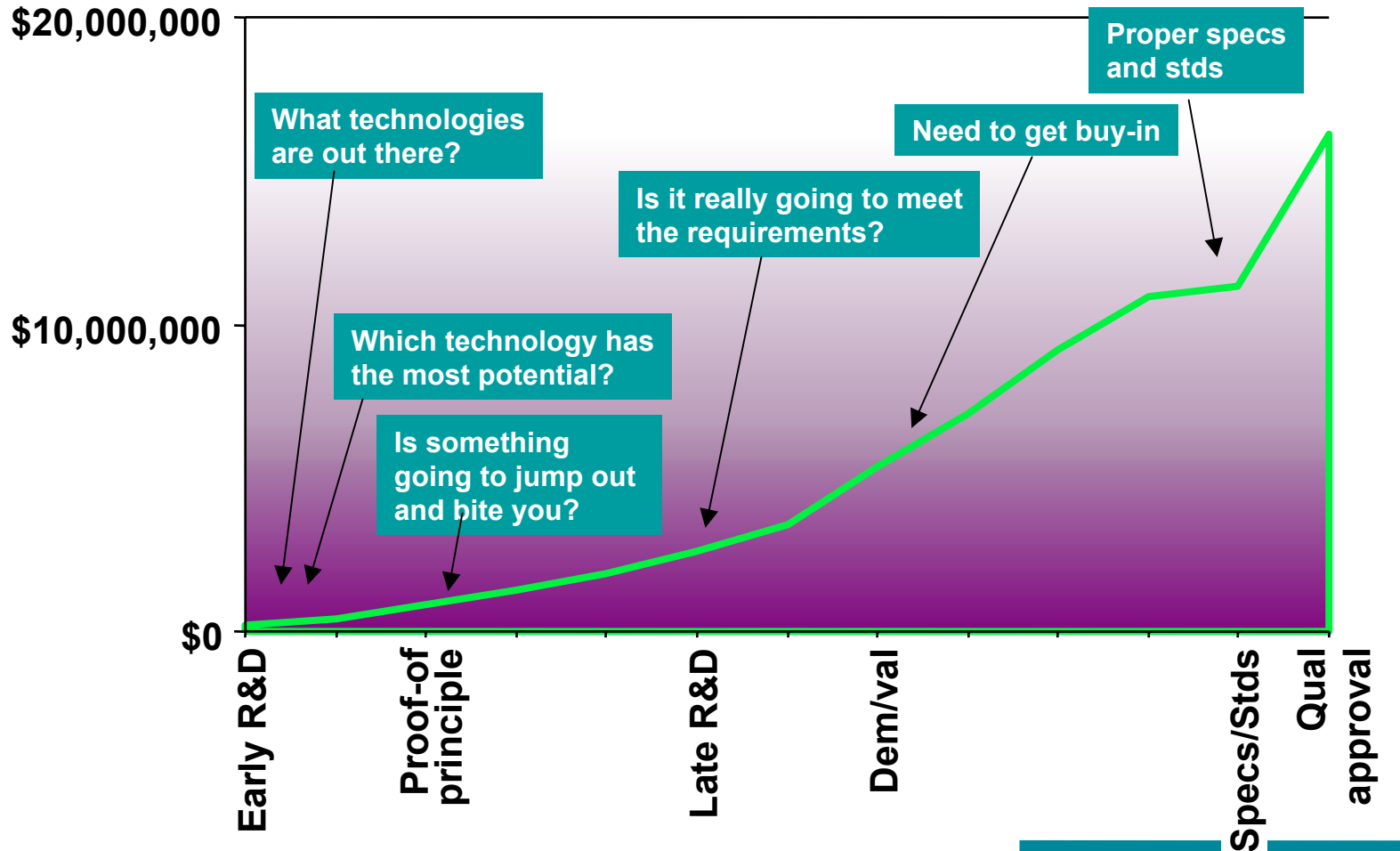
Military landing gear repair not yet qualified



Plasma spray for aircraft IDs >3" - still in development



Getting technology from lab to life



Chrome replacement with thermal spray

Chrome replacement on ODs and IDs - landing gear, hydraulics, etc.

❑ Requirements

- Diameters 0.5-11", lengths 2-100"
- Thickness from 0.0003" (thin dense Cr) to 0.015" (rebuild)
- Low fatigue debit
- Good adhesion, wear

Immediate

Short term

Longer term

These options already in production for specific components

❑ Options

- Electro(electroless) plated alloys, composites
 - ❑ most are Ni-based (next against the wall)
 - ❑ Co-based alloys/composites
- HVOF WC-Co, WC-CoCr, other materials
- ODs
 - ❑ IDs > 2.5"
- Plasma spray Tribaloy, WC-Co
- Electrospray Deposition ESD
 - ❑ Small areas, repairs, ID < 2"

Typical OD chrome applications



Nose landing gear



Main landing gear

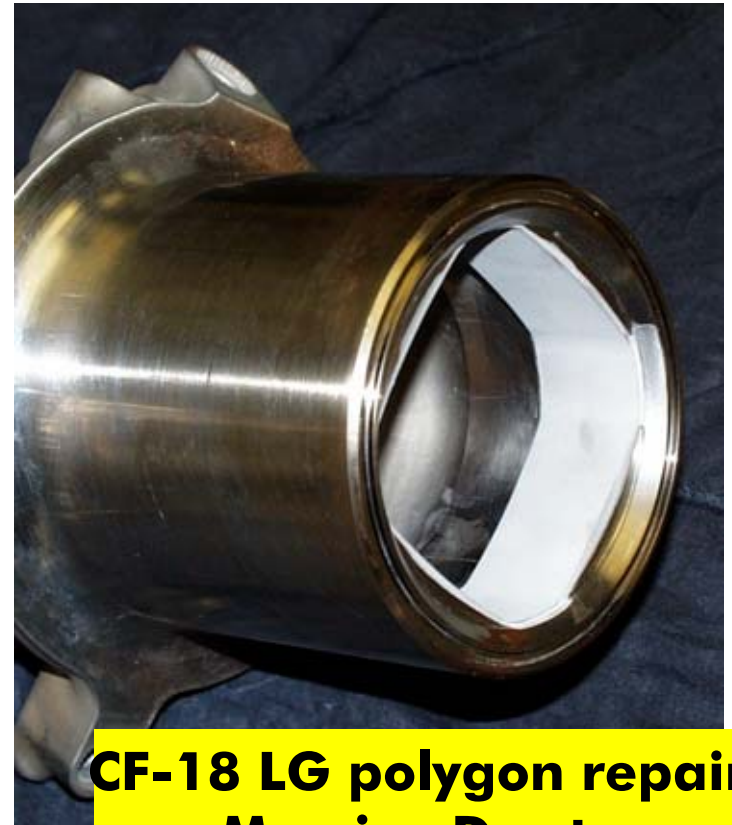
LG frequently use chrome and Cd
on both OD and ID

Existing ID thermal spray applications



**CH-53 blade damper
3.5"ID x 6"long
T400 plasma spray**

- ❑ **Can coat ID if small aspect ratio**
- ❑ **Limited ID usage of plasma spray**
- ❑ **Parker now using thermal spray instead of Cr on new actuators**



**CF-18 LG polygon repair
Messier-Dowty
HVOF from outside**

Chrome replacement with electroless and electrolytic alloys/composites

❑ Alloys

- **Electroless Ni-P, Ni-B are standard materials**

- ❑ **thickness is self-limiting**
 - not good for rebuild
- ❑ **heat treating needed to attain good hardness**
- ❑ **fatigue debit similar to Cr**

- **Being evaluated by AFRL and NDCEE for ID Cr replacement**
- **Nanograin Co-P and other alloys under**

Ni is on the EPA 17 list
Regulation currently low
Likely to be next against the wall

Widespread commercial production
Qualified for aerospace and other use

❑ Composites

- **Ni-SiC, Ni-diamond, etc**
- **Ni-PTFE for lubricity**
 - ❑ **Ni-SiC-PTFE for hardness and lubricity**
- **various commercial suppliers**

- ❑ **Boeing gave up on Takada process (electro Ni-W-B-SiC)**

- **difficult to control**
- **problems with particles in liquid and air handling**

- ❑ **New approaches being developed by NRC, technology@nrc.com, Montreal**

What about gun tubes?

Chrome replacement - gun tubes

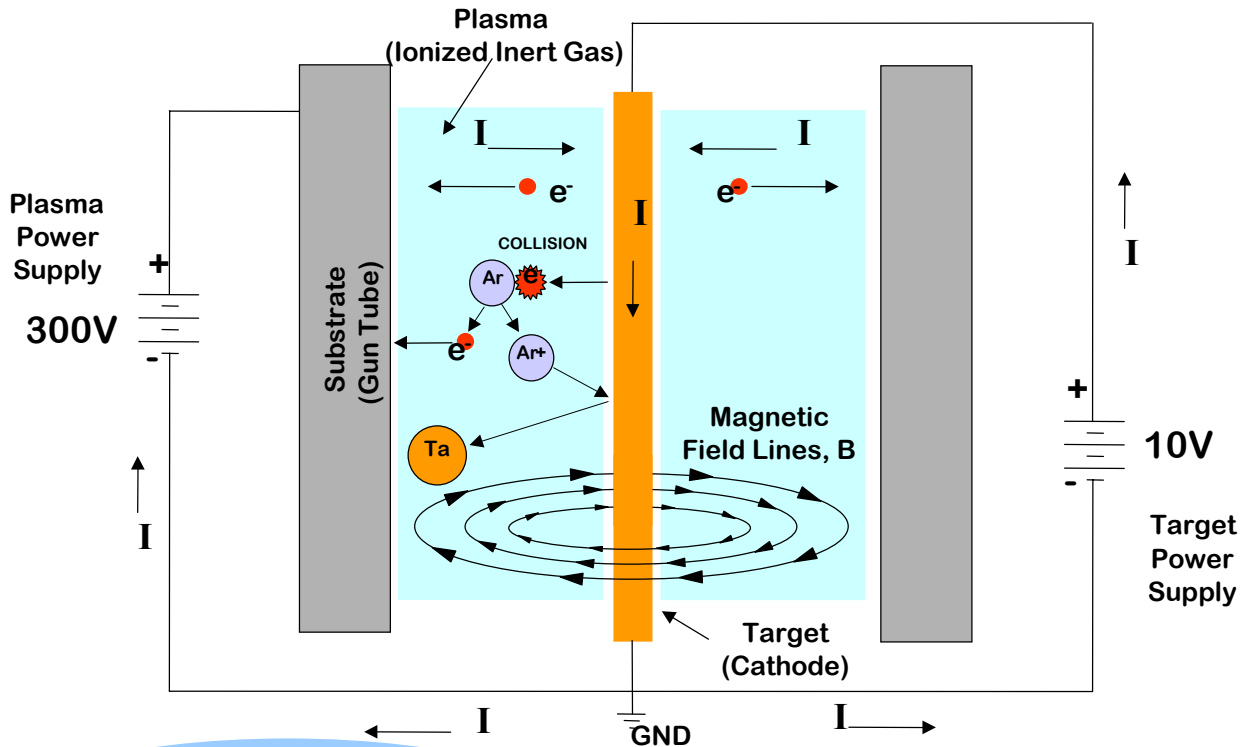
❑ Requirements

- **ID coating**
 - ❑ coat into rifling
 - ❑ little or no finishing
 - ❑ in some cases withstand extrusion/forming
- **Wear/abrasion against shell casing**
- **Erosion/ablation by hot gases, particles from propellant**

❑ Options

- **Sputtered Ta (Green Gun Barrel - Benet Labs)**
- **Electrospark Deposition - under test (small caliber only)**
- **ID alloy/composite plating (Integran)**
- **Explosive bonding (Sigmabond)**

Gun barrel coating - sputtered Tantalum



Pros:

Smooth coating (no refinish)
Coats all at once
Clean

Cons:

Expensive vacuum process
Difficult to get and maintain α -Ta
High level of cleanliness needed
How do you strip it?

Stage of development:

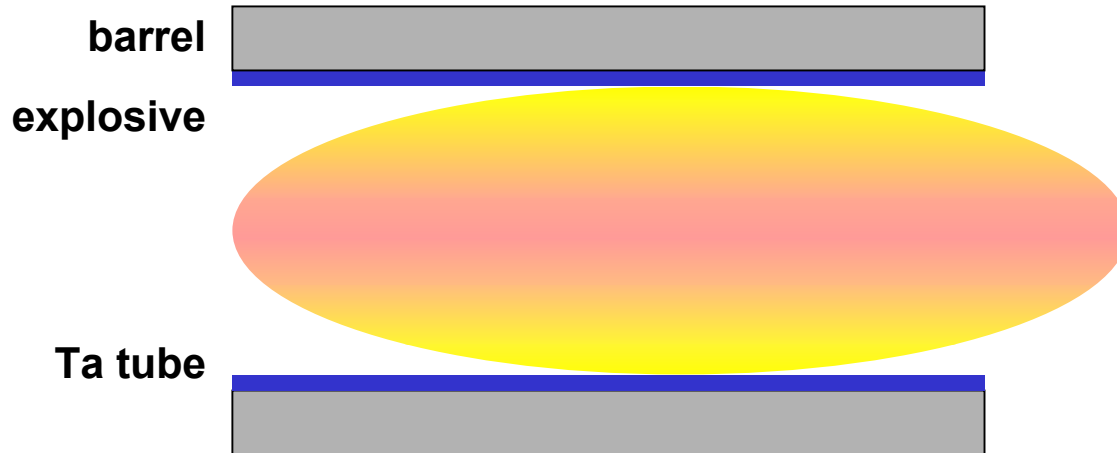
Proof-of-concept
SERDP program
Being installed at OO-ALC for IVD

Vasilikis, Benet Labs
Marshall Labs

New versions replacing high current with magnet array

Same method for IVD - Boeing

Gun barrel coating - explosive bonding



Pros:

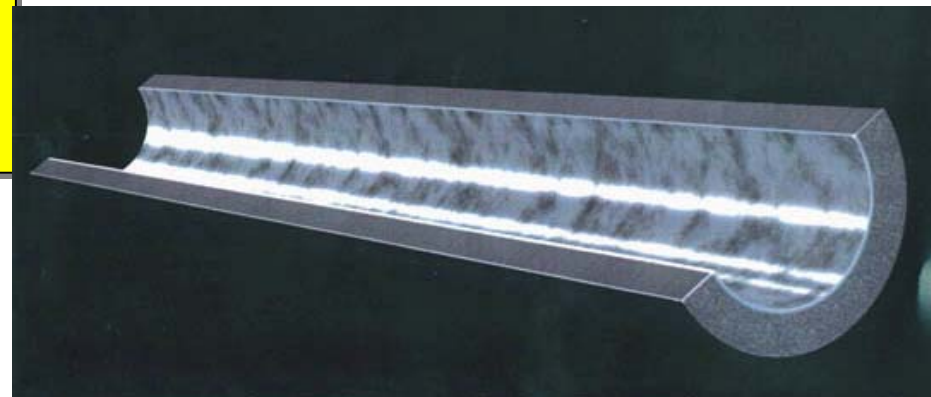
- Fast and fun!
- Penetrates rifling
- Metallurgical (weld) bond
- Works in air
- Could be supplied as a "kit"

Cons:

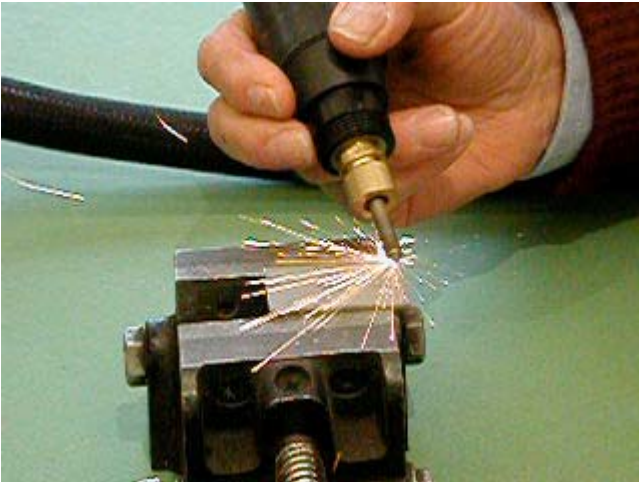
- Few locations can handle explosives
- Sawtooth interface - improper processing will ripple surface
- How do you strip it?

Ta (or other) tube lined with explosive
Explosion front welds tube to barrel over entire surface
Contaminants blown out from interface
Design better alloy materials?

Sigmabond, Canada
Dynamic Materials, CO



Gun barrel coating - Electrospark deposition



Micro-arc welding - manual or auto
Metals, alloys, cermets
Used in nuclear power industry and
GTE repair (P&W)

Pacific Northwest National Lab
Advanced Surfaces and Processes

Pros:

Done in air - auto or manual
No emissions (some powder)
Low temperature process
Metallurgical bond
ID coating as small as 0.5"
Can be extruded after coating
Low capital cost

Cons:

Slow - for small caliber only
Rough surface
Prone to cracks

Stage of development:

Proof-of-concept
SERDP program
Qualified for GTE repair (P&W)

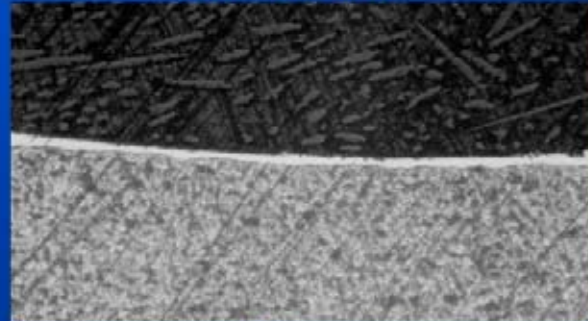
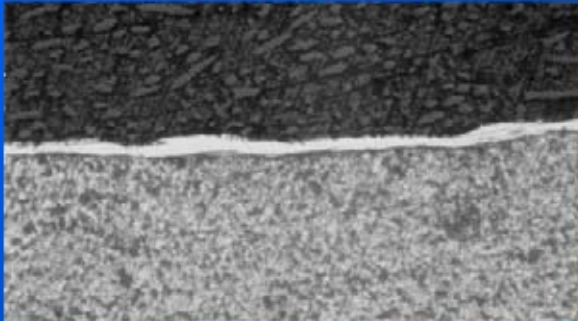
ESD coating of 5.56mm barrel

Squad Automatic Weapon – M249



Before Forging

After Forging

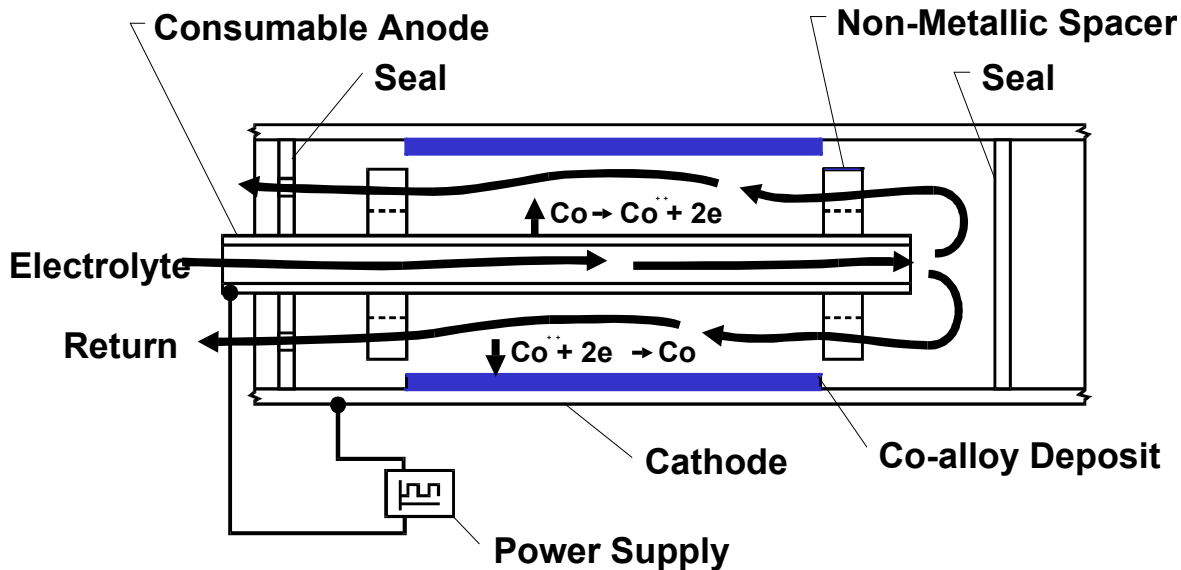


Test coating:
Initial smooth bore
coated before
forging - large
strain, no
delamination.
No test firings yet.



Advanced Surfaces
And Processes, Inc.

Gun barrel coating - Co alloy electroplate, electrocomposites



Pros:

- Smooth coating (no refinish)
- Can coat without long tank
- Very hard nanograin materials
- Thermally stable

Cons:

- Difficult seal against rifling
- Will it remain stable?

Pulse electroplating using cell
Can plate straight and curved tubes
Ni "Electrosleeve" repairs nuclear boiler tubes

Also for plating,
repair of
cooling tubes

Integran, Canada
NRC, Canada

Stage of development:

- Proof-of-concept
- SERDP program
- Ni ID plate used for reactor boiler tube repair (B&W)

Cadmium replacement

Cadmium replacement

Components

- ❑ **The “cure-all” corrosion coating**
- ❑ **Good salt spray and scribed corrosion protection**
- ❑ **No hydrogen embrittlement or stress corrosion cracking**



Fasteners

- ❑ **Correct lubricity (avoid changes to torque-tension specs)**
- ❑ **No hydrogen embrittlement**
- ❑ **Retain thread profile**



Connectors

- ❑ **Solderable**
- ❑ **Low contact resistance**
- ❑ **Non-insulating corrosion products**



JSF - Cd replacement technologies examined

❑ Electroplating methods

- Zn-Ni (acid and alkaline)
- Sn-Zn
- Al-Mn
- Electroplated Aluminum (Alumiplate)

Electroplates

❑ Dry coating methods

- IVD Aluminum and other PVD methods
- CVD aluminum
- Thermal spray aluminum
- SermeTels (Al-ceramics in binders)
- Metal-filled polymers

Everything else

❑ New stainless steels

Al is the only “global” replacement
Dissolution and embrittlement issues

Aqueous electroplates

❑ Pros

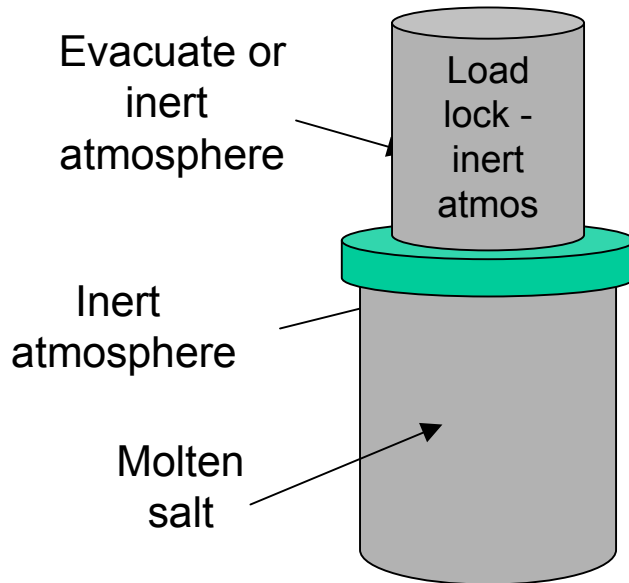
- **Tank methods**
 - ❑ **Closest to drop-ins**
 - ❑ **Large body of available data**
 - ❑ **Currently under some of the most serious evaluation - Boeing**
 - ❑ **WR-ALC has replaced Cd with Zn-Ni and IVD**
 - ❑ **Good throwing power**
- **Usually less expensive than dry methods**

❑ Cons

- **Larger waste volumes than dry methods**
- **Alloy plating can be tricky since chemistry usually depends on solution chemistry and current density**

**Zn-Ni and Sn-Zn
are already in use**

Non-aqueous electroplates - molten salt bath Al-Mn



Pros:

- Good corrosion resistance
- No H embrittlement

Cons:

- Requires enclosed tank
- Temperature too high for Al alloys (including Al connector shells)
- Residual salts can cause environmental H embrittlement
- Plating chemistry uniformity

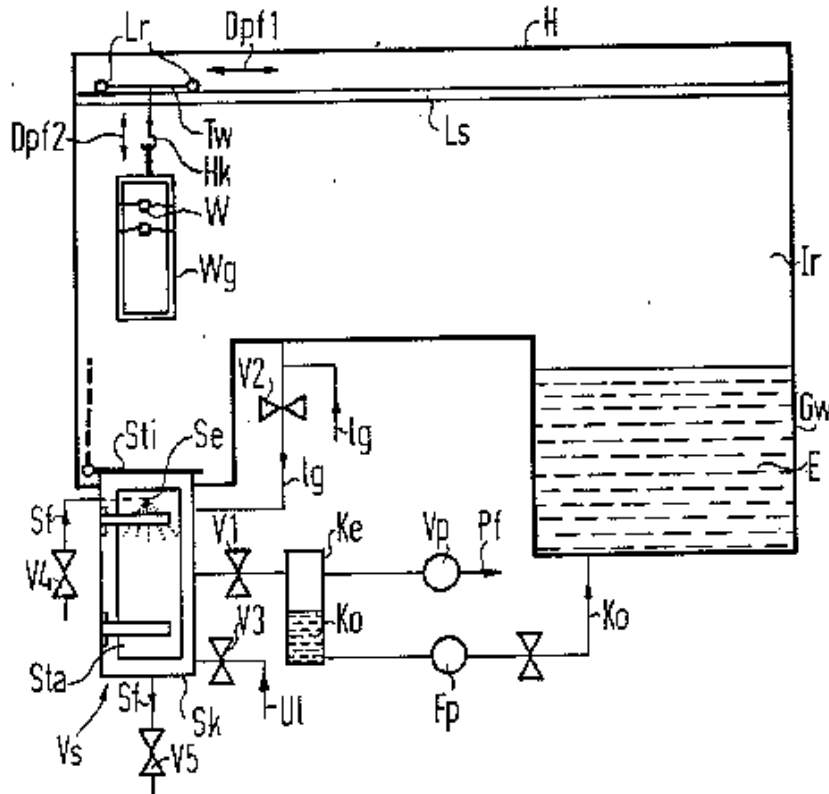
Electroplating from molten AlCl_3 ,
 MnCl_3 bath 350 F

NAVAIR-PAX

Stage of development:

Dem/val (ESTCP program)

Non-aqueous electroplates - organic solvent bath (Alumiplate)



Pros:

- Excellent corrosion resistance
- No H embrittlement
- Looks good for components, fasteners, maybe connectors

Cons:

- Potentially dangerous bath (flammable solvent)
- Requires enclosed tank
- Sole production source (likely to begin licensing)

Stage of development:

- Commercial
- Under extensive DoD evaluation

Electroplating using organic Al salt in a toluene bath

Alumiplate

IVD Aluminum (Ivadizing)



Vacuum evaporation of Al
Bead blasting to densify
Chromate conversion

Abar Ipsen
Depots

Pros:

Long history of successful use
Clean process (except chromating)
High volume chamber (up to 5'x1.5'x15' load)

Cons:

Vacuum process - expensive
Requires shot blasting and
chromate conversion
Poor throwing power (especially in
holes)
Solid lubricant for torque-tension
Limited data on fasteners, electrical
connectors

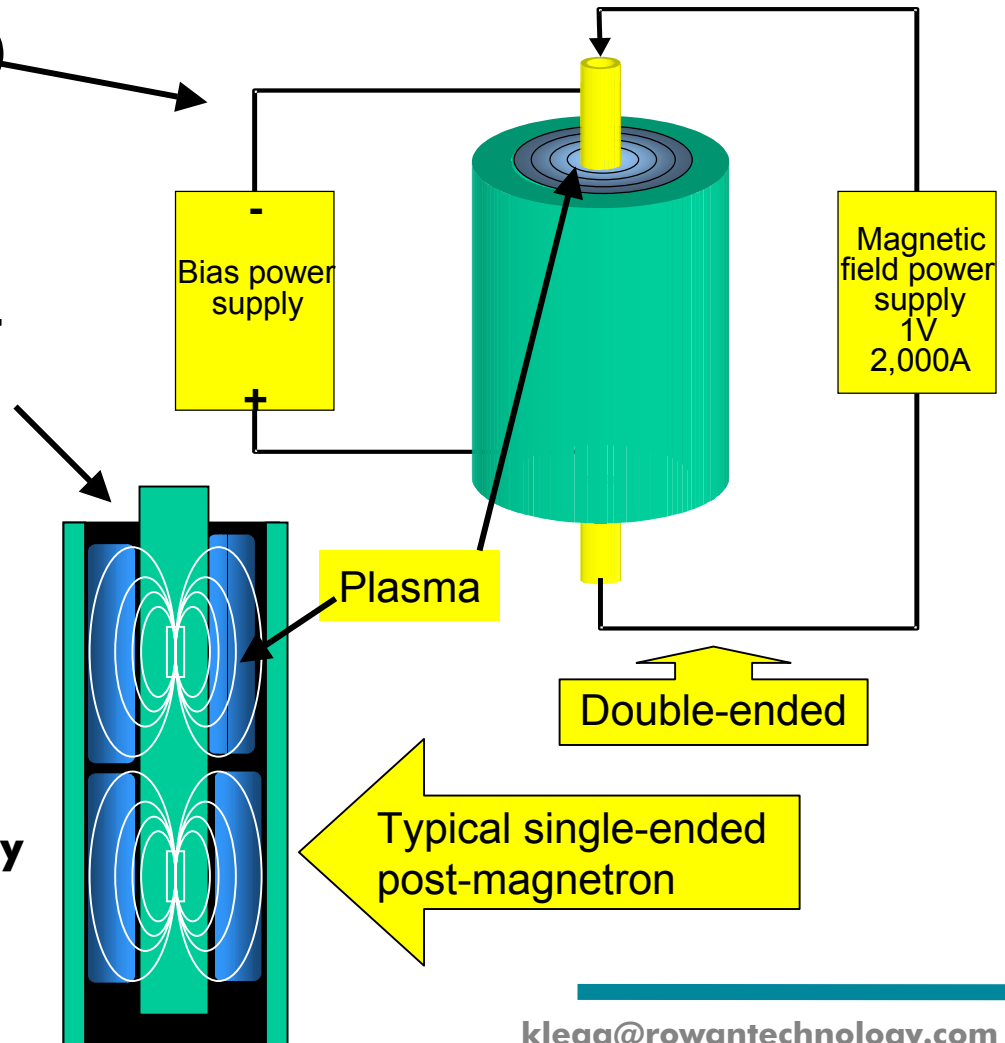
Stage of development:

Commercial
Available at many depots

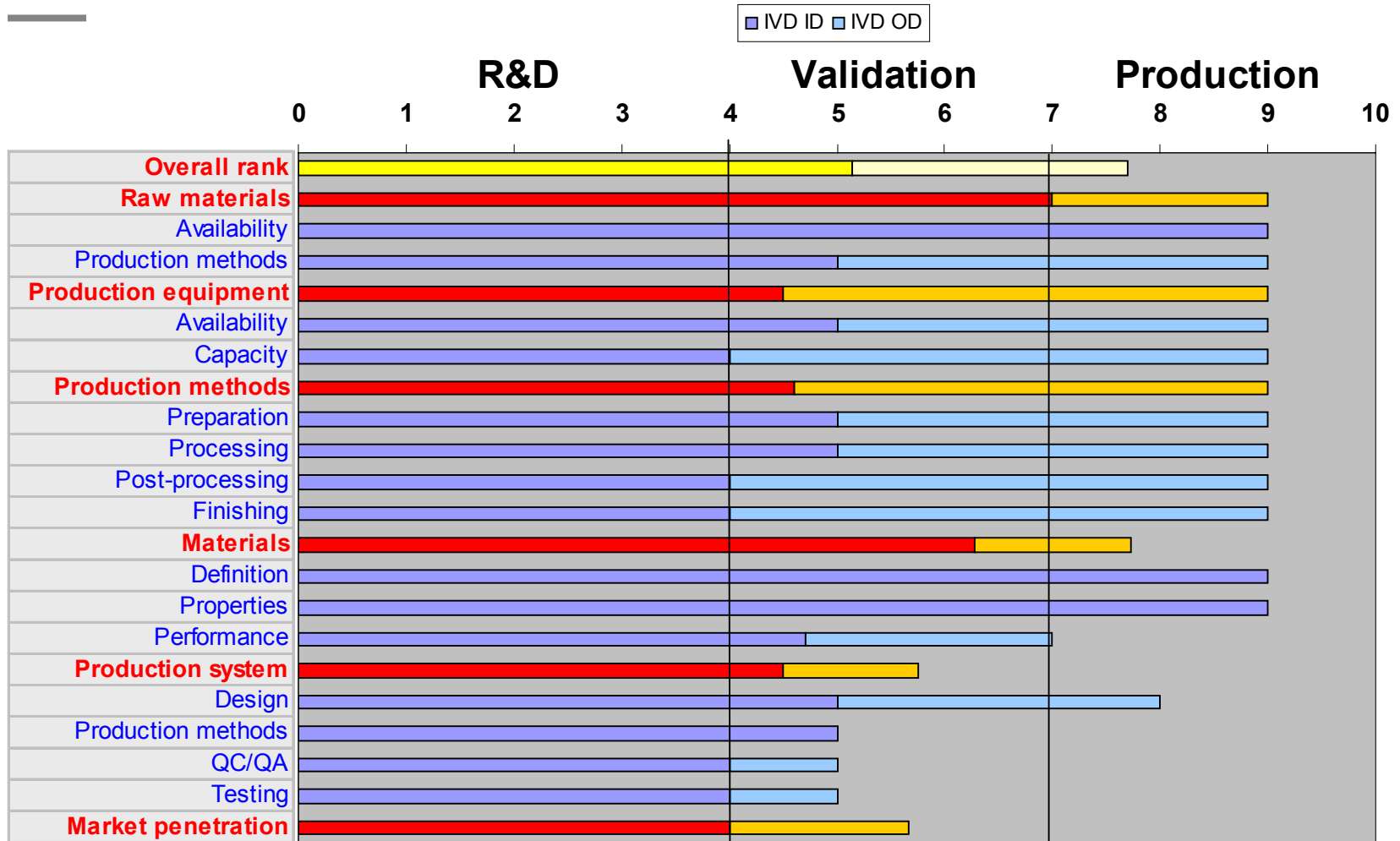
Sputtered aluminum for IDs

- ❑ **Green gun barrel (Benet)**
- ❑ **New types of magnetron equipment (rod magnetron, Plug & Coat)**
 - **Currently under demo at Boeing, St Louis for Hill AFB**
- ❑ **Better coating quality than IVD**
 - **higher plasma density**
 - **lower porosity**
 - ❑ **no need for shot blast**
 - ❑ **may be able to get away without chromating**

Surface Solutions,
Benet Labs



Technology Assessment Matrix - IVD AI



Thermal sprayed Al and alloys



Pros:

Al, Al-Zn already used on some landing gear and infrastructure (bridges, etc.) in Europe
Commercially available
In-air robotic or manual
Able to coat large areas
Spec'd for some landing gear

Cons:

Not for fasteners or connectors
Quite thick (several mils), rough, relatively porous coating
Line of sight

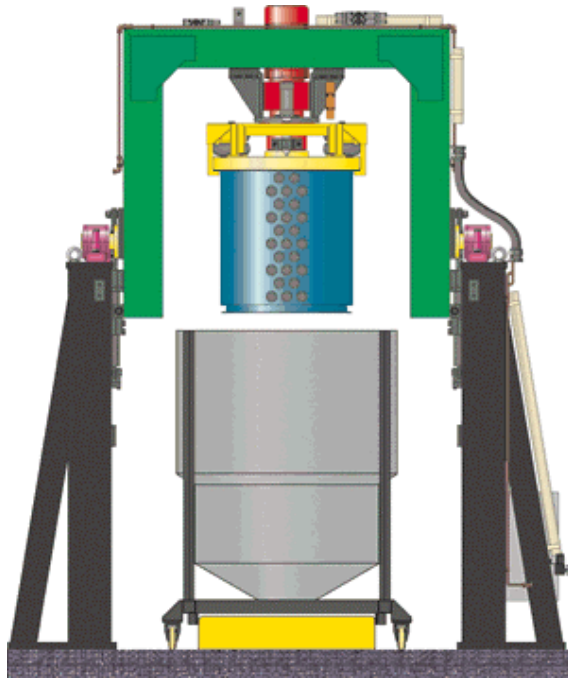
Stage of development:

Commercial

Arc, flame, plasma spray - manual or robotic

Many vendors

Metal-filled polymers for fasteners



Dip-spin or spray
Al- or Zn-filled PTFE or epoxy

Many vendors

Pros:

Inexpensive
Wide automotive use
No embrittlement
Fared very well in TACOM tests

Cons:

Process control
Tends to fill threads
What about lightning strikes?

Stage of development:

Commercial
Wide automotive use

Forget all this coating stuff - just use a better alloy

- ❑ **New computational method (QuesTek Innovations, LLC)**
 - **Materials by Design approach**
 - **Designing stainless steel with essentially the same mechanical properties as 300M**
 - ❑ **Drop-in replacement**
 - **Designer alloys can be made quickly and efficiently (months instead of years)**
 - ❑ **Greatly reduced time-to-design**
- ❑ **New stainless landing gear steel being developed under SERDP and ALGLE funding**
- ❑ **More efficient steels**
 - **Lower alloying (Cr) and carbon percentages**
 - **Designed properties for better performance**
- ❑ **Reduce or eliminate hydrogen embrittlement and stress corrosion cracking**
 - **Primary landing gear mechanism**

Designer steels may be cost-effective for niche applications

New steels - on the other hand

- ❑ Previous stainless steels suffered pitting corrosion
 - Not yet known whether these will do same

- ❑ Initial data suggest not

- ❑ **Will corrode Al alloys**

- ❑ **Cost of qualification may be higher than for a coating**

- To be determined
 - Designers/users must feel comfortable with the steel itself

- ❑ On other hand, if bulk properties look good, avoidance of coatings could reduce testing

- ❑ **Makes sense for new designs - what about legacy systems?**

- Landing gear O&R appear willing to replace existing 300M gear

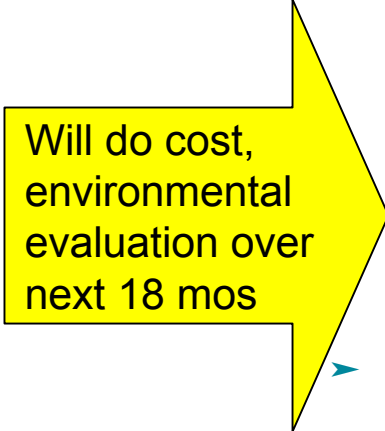
- ❑ **avoids scc - major failure mechanism**

- ❑ probably better damage tolerance

- True drop-in would presumably be acceptable for other components

- ❑ likely to be used mainly for b.e.r. items (if it ain't broke, don't fix it)

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Will do cost, environmental evaluation over next 18 mos

Summary

Analysis

- ❑ Have a good method to find the critical gaps
- ❑ Evaluate best technology, cost, time to production

Gun barrels

- ❑ ID sputtering
- ❑ Ni- and Co-based nanograin electro-plate
- ❑ Explosive welding?

Chromium

- ❑ HVOF coating of choice for ODs
- ❑ For IDs best option depends on diameter
 - electro- and electroless alloys and composites (mostly Ni-based)
 - ESD for small dia
 - plasma spray for large dia

Cadmium

- ❑ Al is “general alternative”
- ❑ Zn-Ni and Sn-Zn electroplates are most developed
- ❑ Non-aqueous Al and Al-Mn
- ❑ Niche options
 - thermal spray
 - metal-filled polymers
 - designer alloys