Benefit Cost Analysis:
ESTCP Funded Cold Spray Technology for DOD Applications

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Thomas Pelsoci, Ph.D.
Delta Research Co.
tpelsoci@deltaresearchco.com

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Cold spray is an environmentally friendly repair technology that can effectively reduce NMC (non-mission capable) rates for DOD aviation and submarine assets. It is a cost effective technique to avoid the replacement of high value, high lead time gearboxes and housing components prone to excessive corrosion and wear. It was developed with early ESTCP funding that led to subsequent DOD investments used to support its implementation across DOD maintenance depots. Benefits include avoiding environmental damage from the primary production of magnesium; annual cost savings of over $23 million; a 9:1 benefit to cost ratio on DOD investments; and substantial reductions in the number of non-mission capable aircraft across the DOD.

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Environmental Security Technology Certification Program (ESTCP) and the Weapons; Systems and Platforms Office in ESTCP; Army Research Laboratory Center for Cold Spray; AH-64 PEO AVN (US) Redstone Arsenal; Aviation Engineering Directorate (AED), AMRDEC Redstone Arsenal; UH-60 U.S. Army Utility Helicopters Project Office (UHPO); F-16 System Program Office; B-1 System Program Office AFLCMC/WWNLD Tinker AFB; PSNS & IMF (Puget Sound Naval Shipyard – Intermediate Maintenance Facility); NAVAL Air Systems Command Materials Engineering Division, Patuxent River; Fleet Readiness Center- East, Boeing; AH-64 Apache Component Engineering, Mesa AZ; Sikorsky Aircraft Corporation; United Technologies Research Center, East Hartford CT; H. F. Webster Engineering Services, Webster MA, and Rowan Technology Group.

EXECUTIVE SUMMARY

Magnesium and aluminum gearboxes and housings on DOD aviation and submarine assets experience significant corrosion and wear problems. Traditional repair methods are generally ineffective and high value gearboxes and housings are often decommissioned and replaced at considerable cost and with long lead times.

Without adequate repair technologies, instances of excessive corrosion and wear can lead to un-acceptably high NMC (non-mission capable) rates for aviation and other assets and represent a major DOD sustainment problem.

The cold spray (CS) repair technology was developed and introduced as a cost effective solution to this major sustainment problem and is currently being implemented across Army, Navy and Air Force maintenance depots.

Cold spray is an additive manufacturing process to deposit material layers for the dimensional restoration of corroded and worn parts. Instead of using heat to bind together the additive material with the substrate, a powder of the additive material is accelerated at supersonic speeds and impinged onto the substrate. In this manner, cold spray does not induce thermal stresses in the parent material. The new layer in combination with the original substrate can be comparable to the strength of the original substrate.

During the early development of the cold spray technology, ESTCP funded a qualification, validation and demonstration project for cold spray repairs of magnesium aerospace components. Results from the ESTCP funded project opened the door for subsequent DOD investments to (1) expand applications beyond magnesium components to parts made from aluminum, stainless steel and titanium and to (2) support the implementation of cold spray repairs across the DOD.

The ESTCP investment was an important catalyst and is reported to have had wide ranging impact. It informed ongoing technical development of CS production systems and kick-started cold spray implementation by the UH-60, AH-64, H-1, F-18, and B1-B program offices. It also stimulated interest by the NAVSEA submarine community which is subject to corrosion induced damage on mission critical parts.

The current state of cold spray implementation is robust.

- Thirteen applications across the three Services have been approved for cold-spray repairs. For each application, DOD aviation assets are currently flying with parts and components repaired with cold spray.

- There are 15 cold spray production systems at various DOD locations. It is expected that additional production systems will be stood up at Camp Pendleton, Ellsworth AFB, Dyess AFB, Portsmouth Naval Shipyard (PNS) and at Corpus Christy Army Depot (CCAD). Existing and planned production systems have sufficient capacity to handle current and projected future workloads.

CS repairs generate significant DOD benefits. It is an environmentally friendly technology that can lead to substantial cost savings. It can also improve operational readiness levels and increase DOD mission capabilities for training and combat missions.

Environmental Benefits

Cold spray can be used to reduce environmental damage associated with primary production of magnesium and the utilization of chromated surface treatments.

Primary Production of Magnesium

With cold spray repairs, it is possible to avoid the replacement of magnesium components with new components made from primary magnesium.

- For each ton of primary production (from MgO ores), 17.8 tons of carbon equivalents are generated
- The mining, refining, and recycling of rare earth elements (which are added to magnesium alloys to make them stronger) also have significant environmental consequences, if not properly managed. One hazard is radioactive slurry tailings from the common occurrence of thorium and uranium in rare earth ores. Another is the use of, toxic acids in the refining process. These environmental risks can be reduces when cold spray repairs are used to avoid the replacement of magnesium castings and housings.

Chrome Reduction

Magnesium is an electrochemically active metal and must be protected against galvanic corrosion when coupled with other metals in the presence of an electrolyte.

To protect sealing or mating surfaces, the standard practice is to hard anodize the surface with chromated Dow 17 or use a chromated conversion coating, followed by a sealant compound. To protect non-sealing surfaces, the standard practice is to hard anodize the surface with Dow 17, seal with Rockhard and finish with a chromated primer and topcoat.

It has been demonstrated that cold spray can be used for dimensional restoration without the standard practice of chromated surface treatments.

- For the UH-60 program, a new surface treatment is being introduced for non-structural applications
- Magnesium parts and corroded areas repaired with cold spray will be an anodized with non-chromated TAGNITE.
- However, for non-sealing surfaces, the anodized layer will continue being covered with a chromated primer and topcoat.

There may be an opportunity to migrate away from chromated primers in the near future. Several respondents from aviation program offices referenced an ongoing ESTCP project (WP-201132) to validate the operational performance of non-chromated primers. Respondents continue to monitor this ESTCP funded effort and may be able to implement non-chromated primers that are successfully validated.

Cost Savings Benefits

Cold spray repairs make it possible to avoid the replacement of expensive parts:

- Magnesium castings on UH-60, AH-64 and H-1 aircraft
- Aluminum castings on F-18 fighters and
- Aluminum access panels on B1-B bombers.

In addition, cold spray deposition on B1-B hydraulic tubes (titanium substrate) can reduce substantial maintenance costs associated with excessive chafing wear.

For each application, cold spray repairs will generate substantial cost savings. On an annual basis, cost savings from the 13 approved applications are expected to be $22.5 million. Two additional applications, now moving toward approval, will generate additional cost savings of $970,000. Total savings are estimated at 23.6 million per year.

Annual cost savings are projected over the remaining service life of DOD aviation assets with cold sprayed components. Projections are used to compute two performance metrics for DOD investments in the cold spray technology, Net Present Value (NPV) and Benefit Cost (B:C) ratio.

For a base-case scenario,

- NPV of cost savings is $289.6 million
- B:C ratio is 8.9 to 1, indicating that for each dollar of DOD investment, DOD will realize almost $9 in cost savings

For a more conservative scenario, the NPV is 250.4 million and B:C ratio is 7.8 to 1

For a more optimistic scenario, the NPV is $318 million and the B:C ratio is 9.7 to 1

Comparing performance metrics across alternative scenarios points to robust cost saving across the three scenarios.

- NPV of cost savings range from $250 million to $318 million
- Benefit Cost ratios range from 7.8 :1 to 9.7 :1

Operational Readiness Benefits

Cold spray repairs will reduce depot level backlogs and non-mission capable (NMC) aircraft. These operational readiness benefits are not included in calculations of cost savings. They represent an effective solution to a major DOD sustainment problem and will have a positive impact on DOD training and combat mission capabilities.

Over 4500 helicopters in the DOD fleet have multiple Mg gearboxes which are highly susceptible to corrosion and fretting wear. Other flight critical parts made from aluminum, stainless steel and titanium are also susceptible to excessive chafing wear, etc.

Corroded and worn gearboxes and housings often cannot be repaired. When components exceed corrosion and wear allowances they are decommissioned and must be replaced with spares from depot inventories or by the procurement of new parts.

If spare parts inventories are insufficient to meet replacement needs, long lead times for the procurement of new Mg and Al components can ground aircraft and reduce the operational readiness of the Force. The problem is exacerbated by supply chain limitations. One example is Magnesium Electron Corp, which is the only U.S. company qualified by Sikorsky Aircraft Co. to manufacture magnesium castings for the UH-60 and AH-64 fleet..

DOD views the replacement of corroded and worn gearboxes and housing as a major sustainment problem which can lead to critical safety and readiness issues.

The cold spray repair technology provides a practical solution to this major sustainment problem. It can be implemented rapidly and cost effectively during in-depot overhaul cycles as well as at field installations and can contribute to

- Fewer condemnations of flight critical components
- Reduced depot level backlogs and costs
- Reduced NMC aircraft and higher on-wing time
- Significantly enhanced operational readiness and
- Enhanced mission capability for DOD aviation assets

Cold spray repairs can also be used to refurbish condemned parts stored at CCAD, FRC-E and other DOD depots and create a spare parts inventory buffer against long lead time procurements for unscheduled repairs.

Parts on aviation assets that are no longer in production are particularly prone to long lead time replacement cycles. For these parts, cold spray repairs and a larger numbers of spares can be used to effectively expand the operational life of aviation assets beyond their original service lives.

The overall impact of cold spray repairs will be to significantly increase the availability of DOD aviation assets for training and for combat operations

ACRONYMS

ADG	Accessory Drive Gearbox
AED	Army Engineering Directorate
AFB	Air Force Base
AH-64	Apache Attack Helicopter U.S. Army
ALC	Air Logistics Center
AMAD	Airframe Mounted Accessory Drive
AMRDEC	Aviation & Missile Research Development & Engineering Center
ARL	Army Research Laboratory
B1-B	Lancer Strategic Bomber USAF
CCAD	Corpus Christi Army Depot
CP-Al	Commercially Pure Aluminum
CS	Cold Spray
CSAT	Cold Spray Action Team
CTMA	Commercial Technologies for Maintenance Activities
DemVal	Demonstration & Validation
DOD	Department of Defense
EPRI	Electric Power Research Institute
EMI	Electromagnetic Interference
ESOH	Environmental Safety & Occupational Health
ESTCP	Environmental Security Technology Certification Program
ETAR	Engineering Technical Assistance Request, Ellsworth AFB
EV	Expected Value, Probability of Realization * Nominal Value
EYAB	Boeing Engineering Approval Document
F-18	Super Hornet
FEB	Forward Equipment Bay panels
FRC-E	Fleet Readiness Center – East (Cherry Point)

FRC-SE	Fleet Readiness Center – South East (Jacksonville)
FRC-SW	Fleet Readiness Center – South West (North Island)
H-1	Cobra Attack Helicopter U.S. Marine Corps
IGS	Intermediate Gear Support
MRO	Maintenance, Repair, Overhaul
NAVAIR	U.S. Naval Air Systems Command
NPV	Net Present Value
OEM	Original Equipment Manufacturer
NMC	Non-Mission Capable
PNS	Portsmouth Naval Shipyard
PSNS	Puget Sound Naval Shipyard
PV	Present Value
SAFR	AMRDEC Engineering Storage, Analysis, Failure Evaluation & Reclamation Program U.S. Army
SERDP	Strategic Environmental Research & Development Program
SSN	Nuclear Powered Attack Submarine, U.S. Navy
SSBN	Nuclear Powered Ballistic Missile Submarine, U.S. Navy
TD-63	Actuator on U.S. Navy Attack Submarines
UH-60	Blackhawk Attack Helicopter, U.S. Army
VOC	Volatile Organic Compound
WP	Weapons, Systems and Platforms Program Area in SERDP / ESTCP

INTRODUCTION

The Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) are the Department of Defense's environmental research programs, harnessing the latest science and technology to improve DOD's environmental performance, reduce costs, and sustain mission capabilities.

The programs respond to environmental technology requirements that are common to all of the military Services, promote partnerships and collaboration among academia, industry, the military Services, and other federal agencies and coordinate the full spectrum of efforts, from basic and applied research to field demonstrations and validation.

Weapons, Systems and Platforms (WP) is a program area within SERDP /ESTCP. It supports he development and demonstration of innovative technologies that enable the Department of Defense to reduce or eliminate the use of hazardous materials in its production and maintenance processes, reduce hazardous waste streams, mitigate emissions and other environmental impacts that result from its operations, reduce costs and sustain DOD mission capabilities.

Objectives & Scope

In 2005, WP funded an ESTCP Project (*Cold Spray for Repair of Magnesium Components)* to demonstrate and validate the utility of the innovative cold spray technology for the repair of high value aviation components, subject to corrosion and excessive wear. The ESTCP funded project was completed in 2011.

In 2014, SERDP / ESTCP tasked Delta Research Co. to conduct an independent benefit cost analysis of the cold spray technology, with the following objectives:

- Identify implementation pathways, implementation status and DOD wide utilization of the CS repair technology and
- Identify DOD benefits along the three dimensions of environmental benefits, cost savings, and operational readiness benefits.

The scope of the benefit cost analysis is limited to thirteen cold spray applications that have achieved interim approval status and two additional applications moving toward near term approval. Over a longer time frame, cold pray repair technology is expected achieve approval status for other promising applications. These are noted but not included in the current analysis.

SECTION 1: ANALYTICAL APPROACH

Information for benefit cost analysis is collected from multiple sources, including

- Review of the technical literature about the (1) repair of corroded and worn surfaces on high value aviation parts (2) surface treatment alternatives to protect substrates and cold spray deposits and the (3) environmental impact of alternative surface treatments.
- Structured interviews with program office staff, depot engineering staff, and OEM representatives including subject matter experts at:
  - ARL Center for Cold Spray
  - AH-64 PEO AVN (US) Redstone Arsenal
  - Aviation Engineering Directorate (AED), AMRDEC Redstone Arsenal
  - UH-60 U.S. Army Utility Helicopters Project Office (UHPO)
  - F-16 System Program Office
  - B-1 System Program Office AFLCMC/WWNLD Tinker AFB
  - PSNS & IMF (Puget Sound Naval Shipyard – Intermediate Maintenance Facility)
  - NAVAL Air Systems Command Materials Engineering Division, Patuxent River,
  - Fleet Readiness Center East
  - Boeing, AH-64 Apache Component Engineering, Mesa AZ
  - Sikorsky Aircraft Corporation
  - United Technologies Research Center, East Hartford CT
  - H. F. Webster Engineering Services, Webster MA

Structured interviews are used to discover new information and obtain insights into cold spray development and implementation on a Service by Service basis. Discussion topics include:

- State of the technology; applications development for magnesium and other substrates; production systems with nitrogen and helium carrier gases; nozzle designs; supply chain issue; technical performance of cold spray applications "flying" on Army, Navy and Air Force aviation assets; etc.
- Implementation; investments in production systems both stationary and portable; approvals of cold spray applications; promising future applications, etc.
- Environmental impact; compatibility with non-chromated surface treatments; recycling magnesium parts; primary production of magnesium from MgO ores; etc.
- Cost saving opportunities; number of replacements of corroded and worn housing units that could not be repaired without cold spray depositions; cost of replacement parts; logistics costs for unscheduled repairs; cost of cold spray depositions; etc.
- Operational readiness benefits; depot level backlogs and extended maintenance cycles; availability of spares to replace corroded and worn housing parts; procurement lead times to replace parts; etc.

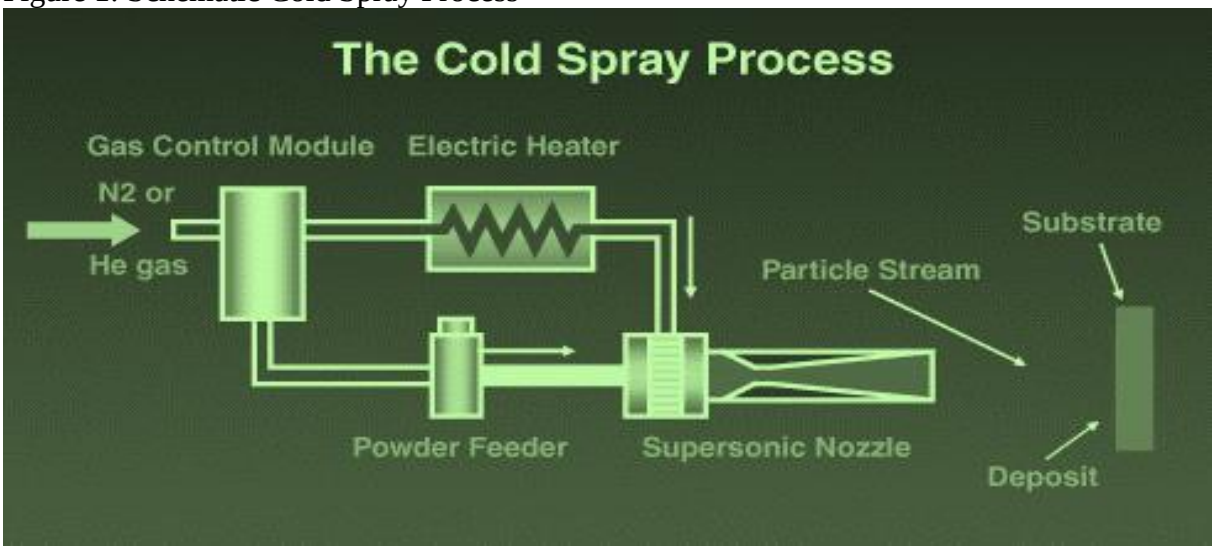
During the analysis stage, annual costs savings are identified and projected over the remaining service life of aviation assets for which cold spray repairs have been approved. Projected cost savings are used to calculate economic performance metrics. i.e., the Net Present Value and Benefit Cost Ratio. Performance metrics are computed for three scenarios, a base case scenario, a more conservative scenario and an optimistic scenario.

SECTION 2: ESTCP FUNDED COLD SPRAY TECHNOLOGY

Cold spray (CS) is a powder consolidation process whereby metallic, polymeric and/or combinations of metallic and non-metallic particles are consolidated to form a coating or a near-net shaped part by means of ballistic impingement upon a suitable substrate. To date the cold spray process has been used primarily for dimensional restoration and to apply wear and corrosion resistant coatings.

Advances in the development of feedstock powders, process parameters and production equipment have enabled the production of bulk cold spray materials with superior properties, including; increased strength and ductility comparable to those of wrought materials. When utilized to produce a coating, the new layer in combination with the original substrate can be comparable or greater than the strength of the original substrate. Figure 1 provides an overview of the cold spray process

Figure 1: Schematic Cold Spray Process



Some other advantages of the cold spray supersonic deposition process include

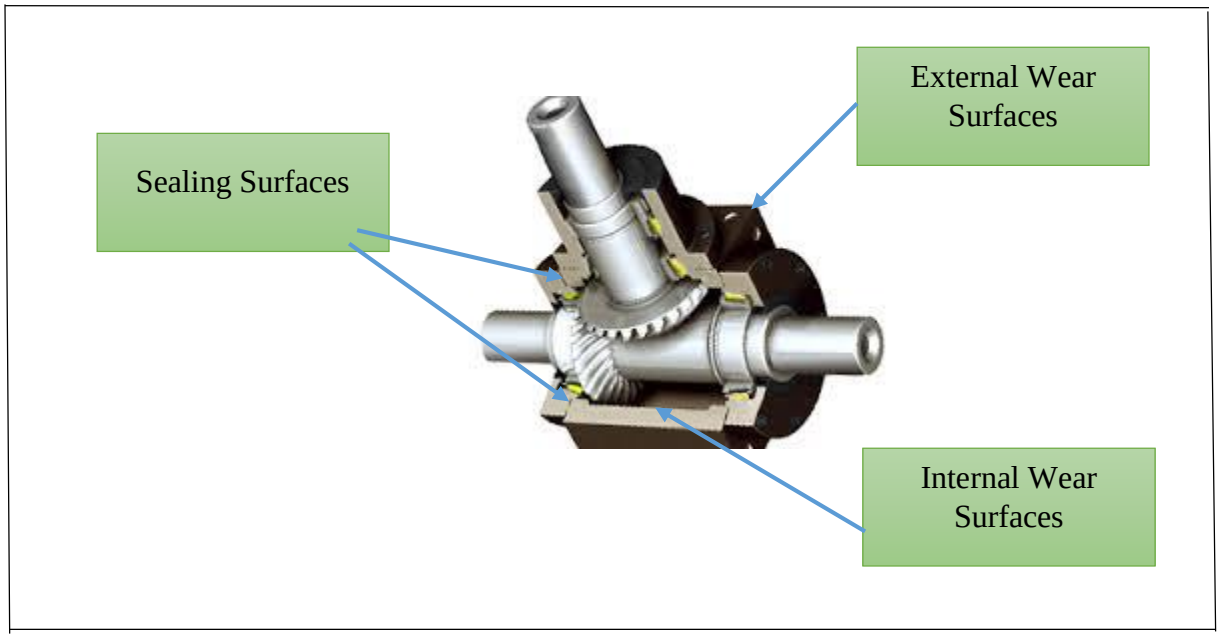
- Low temperature process, below the melting point of the powder particles and the substrate
- Solid state bonding, resulting in mechanical mixing of particles and substrate similar to explosive bonding
- High density deposit at high deposition rates forming thick deposits
- Low oxide and porosity content
- Environmentally friendly process, without combustion fuels, harmful emissions and volatile organic compounds (VOC's)
- Process can be portable for use in remote locations
- In stationary configuration, process can be robotically controlled

These unique attributes make cold spray compatible with many aerospace materials, including magnesium, aluminum, steel, bronze, titanium and stainless steel components.

Common Applications

One generic application is the restoration of sealing surfaces and wear surfaces on gear boxes. Figure 2 displays a generic gear box with sealing and wear surfaces indicated.

Figure 2: Generic Gear Box



Gear boxes are composed of multiple pieces with mating surfaces that must achieve a tight seal to avoid leakage of lubricating oils. A combination of galvanic and crevice corrosion is the primary damage mechanism for mating surfaces on Mg alloy gearboxes. Most corrosion occurs at attachment points such as lugs and mounting bolts (as well as flanges and mounting pads) where a dissimilar metal is in contact with magnesium substrate.

To prevent failure and leakage at mating surfaces, maintenance specifications identify maximum allowable depths of corrosion and wear damage consistent with desired safety factors. When maximum allowable damage is exceeded, the part must be repaired or replaced.

Traditional repair technologies include

- Aluminum shims or washers glued in place of the missing Mg alloy. The shims cannot carry load and thereby weaken the Mg structure
- Using heat to fuse new metals to the Mg substrate, potentially inducing undesirable thermal stresses and leading to the decommissioning of high value gearboxes

In contrast to traditional repair methods, cold spray is an additive manufacturing process which adds metal powders accelerated at supersonic speeds to restore the original substrate after the corrosion or other defect have been removed. The cold working that occurs during cold spray results in combined yield strengths equal to or greater than the strength of the underlying magnesium substrate.

Currently approved cold spray repairs are for non-structural components. These components are not subject to high flight loads and are not fatigue sensitive. Non-structural components do, however, carry other loads, including the weight of an entire assembly enclosed in a gear box or transmission box, repaired with cold spray.

As future application opportunities arise, it must be recognized that cold spray is not a general "drop in" solution. New applications require the deposition of new materials on different substrates, are subject to different performance standards, and may require new processes and new standardization initiatives.

Increasing the reach of the innovative cold spray repair technology within DOD requires ongoing investments for development, testing and validation specific to new applications.

SECTION 3: IMPLEMENTATION STATUS

This section is organized in five headings:

- Leveraging early ARL and ESTCP investments with additional DOD funding
- Approved parts for cold spray repairs (UH-60, AH-64, F-18, H-1, and B-1B)
- Organization of cold spray R&D and implementation efforts
- Cold spray production capacity investments and
- State of DOD implementation

Leverage for Ongoing Development

The Army Research Laboratory led early DOD efforts to develop and implement the cold spray technology for surface repairs on aviation assets. ARL championed the technology, disseminated information, and led standardization efforts (See Appendix B).

The ESTCP provided early funding to support a DemVal of the cold spray technology for the dimensional restoration of magnesium castings.

ARL and ESTCP funded $7.5 million and $1.5 million, respectively. Their combined $9 million investment spurred $27.6 million of additional DOD investments, representing an over three fold leverage relative to early stage ARL and ESTCP investments (See Table 1).

Table 1: DOD Funding for Development and Implementation of Cold Spray Technology

ARL	7,500,000
ESTCP	1,500,00
EARLY FUNDING	9,000,000
OSD MANTECH	5,100,000
DLA Aviation Program	700,000
Congressional Mandated Funding	17,500,000
ONR Nanotechnology (Powders)	800,000
Toxic Metal Reduction Program	3,500,000
LEVERAGED FUNDING	27,600,000
TOTAL DOD INVESTMENT	36,600,000
LEVERAGE FACTOR (27.6 million / 9 million)	3.1 x

Approved Applications

Early ARL and ESTCP funded projects kick started implementation efforts by the UH-60, AH-64, F-18, H-1, and B-1 program offices and by NAVAIR and USAF engineering units. These implementation efforts resulted in the approval of 12 parts for cold spray repairs and one approval for the deposition of a sacrificial layer to minimize repairs. Two additional applications are moving toward near term approval, the AH-64 Static Mast and the TD-63 Actuator for SSN attack submarines.

ARMY

- UH-60 Sump (MEO B1671 packing seal surface repair)
- UH-60 Intermediate Gearbox (MEO B1089 center, input, output housings)
- UH-60 Tail Rotor Gearbox (MEO B1090 center, input, output housings)
- UH-60 Accessory Gearbox (MEO B1091 cover and housing)
- UH-60 Input Module (MEO B1092 center, input, output housings)
- AH-64 Intermediate Gear Support (EYAB: 12-153 top & outer land repair)
- T-700 Turbine Engine Front Frame (MEO-B1718)

NAVY

- F-18 AMAD Main Housing (hydraulic pad restoration)
- F-18 AMAD Main Housing (gear failure repair)
- F-18 AMAD (Hydraulic Gear Shaft seal surface repair)
- H-1 Combining Gearbox (external chafing repair)

AIR FORCE

- B-1 Forward Equipment Bay (FEB) Panels (ETAR) E12-00248
- B-1 Hydraulic Tube Sacrificial Layer Deposition (ETAR) E09-00065

Note: Army and USAF approvals are specified by formal approval documents (MEOs or Maintenance Engineering Orders and ETARs or Engineering Technical Assistance Requests). NAVAIR approvals are implemented with internal memos from NAVAIR Engineering Department at Patuxent River.

Organizations

The Army Research Lab and the ARL Center for Cold Spray played a sustained leadership role in the early development and validation of the cold spray technology. ARL was a strong champion for standardization and achieving approvals for cold spray applications across the Army, Navy and Air Force.

Other important centers of cold spray development and adoption are FRC-E and FRC-SW, NAVAIR at Patuxent River, Corpus Christy Army Depot, Oklahoma City ALC, Tinker AFB, and Ellsworth AFB.

Investments In Cold Spray Systems

Reportedly, DOD has 15 operational cold spray systems and five additional systems are planned for near term deployment (See Table 2).

Different cold spray systems have different characteristics (high pressure, low pressure, stationary and portable) and require different levels of investments. Only some systems are used as production systems. The remaining are used to continue application development and prototyping.

Table 2: Installed (I) and Planned (P) Cold Spray Systems

Location	Installed (I) Planned (P)	Pressure H or L	Approx. System Cost	Approx. Facility Mod Cost	Use
ARL	2 (I) 4 (I)	H - Stationary H - Portable			R&D Production
Moog Inc., (ARL Contractor)	1 (I) 1 (I)	H - Stationary H - Portable	200K		Production
FRC- E	2 (I) 1 (I)	H – Stationary L	300K 160K	2 Mill	Production
Camp Pendleton	1 (P)	L	160K		Production
FRC-SW	1 (I) 1 (I)	H L - Portable	300K 100K		Production
FRC-SE	1 (I)	L - Portable	100K		Production

Table 2 (Continued)

NAVAIR Patuxent River	1 (I)	L	200K		Test & Eval
Ellsworth AFB	2 (P)	H	450K		Production
Dyess AFB	1 (P)				Production
CCAD	1 (P)				Production
PNS	1 (P)				Production

State of DOD Implementation

Early ARL and ESTCP investments generated substantial momentum for the development of new cold spray applications and for implementing cold spray repairs across the DOD.

- ARL and ESTCP funding support led to $27.6 million of additional DOD investments.
- Thirteen applications across the three Services have been approved for cold-spray repairs and it is projected that annual cost savings from cold spray utilization will reach and likely exceed $23 million (See Section 5, Cost Savings).
- Gearboxes and housings repaired with cold spray are "flying" on aircraft, without reported problems.
- Other applications are progressing toward near term approval or starting the approval process (See Section 4).
- There are 20 cold spray systems at various DOD locations. Fifteen have been implemented. Five systems will be stood up in the near future.
- Existing and planned production systems have sufficient capacity to handle current workloads and projected future workloads.

The state of DOD cold spray implementation is robust and can be expected to ramp up on a pathway of future expansion

SECTION 4: DISCUSSION OF COLD SPRAY APPLICATIONS

To date, twelve applications have been approved for cold spray repairs and one application approved for the deposition of a sacrificial layers to reduce the need for repairs. In addition, two applications are moving toward interim approval (See Table 3).

Table 3: Cold Spray Applications on Aviation and Submarine Platforms

	Approved Applications	Applications Moving Toward Approval
UH-60 Blackhawk helicopter	5	
AH-64 Apache helicopter	1	1
H-1 Super Cobra attack helicopter	1	
GE T-700 Engine	1	
F-18 Hornet fighter	3	
B1-B Lancer Bomber	2	
SSN Submarines		1
Total	13	2

Information about these applications was obtained from Army and Air Force program offices, NAVAIR and FRC-E engineering staff, Army depots, Air Force ALC's, OEMs and DOD contractors.

UH-60 Blackhawk Helicopter

The Sikorsky UH-60 is an attack helicopter used by the Army. It has twin General Electric T700-GE-401C turboshaft engines. There are 2,136 aircraft in the Blackhawk fleet. The aircraft is expected to remain in service until after 2030.

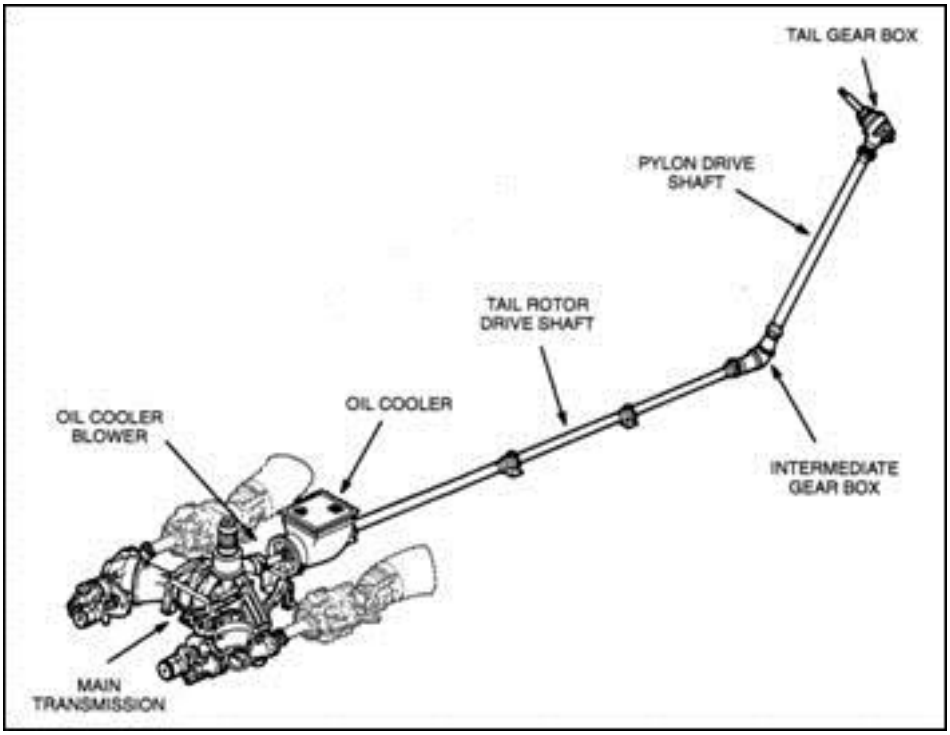
Cold Spray Repairs

There are five approved applications for cold spray repair of corroded magnesium parts, one with final approval (UH-60 Sump) and the other applications with interim approvals.

- UH-60 Sump - packing seal surface repair
- UH-60 Intermediate Gearbox - center, input, output housings
- UH-60 Tail Rotor Gearbox - center, input, output housings
- UH-60 Accessory Gearbox - cover and housing
- UH-60 Input Module - center, input, output housings

To help visualize how approved parts are configured, Figure 3 provides a schematic of gearbox arrangements.

Figure 3: H-60 Transmission System Powertrain



Opportunities for Costs Savings

UH-60 magnesium components arrive at CCAD during the regular maintenance cycle and are disassembled for inspection. Fifty percent of gearboxes are sufficiently corroded to be out of allowance and, in the absence of approved repair methods, gearboxes are replaced at full replacement cost.

Approved cold spray repairs make it possible to avoid the replacement of expensive magnesium castings. Annual cost savings can be estimated as the number of parts decommissioned and replaced times the replacement cost of the new part minus the cost of cold spray repairs. Table 4 summarizes these cost elements.

Depot Backlogs and Aircraft Availability

If spares are unavailable, the replacement of UH-60 magnesium castings requires substantial lead times of up to 6 to 12 months In contrast, cold spray repairs can be completed in a matter of days or weeks and eliminate replacement lead times as a major contributor to depot level delays and backlogs.

Table 4: UH-60 Cost Elements for Estimating Cold Spray Cost Savings

	Unit Replacement Cost	Cold Spray Costs	Replaced per Year
SUMP	14,389	2,000	2
Intermediate Gearbox	36,285	5,000	25
Tail Rotor Gearbox	72,341	3,500	16.3
Accessory Gearbox	35,355	3,000	4.5
Input Module	84,351	5,000	5

Sources: Army Maintenance Management System – Aviation.

AH-64 Apache Helicopter

The Boeing AH-64 is an attack helicopter used by the Army. It has twin General Electric T700-GE-401C turboshaft engines. There are approximately 700 aircraft in the Apache fleet. The aircraft is expected to remain in service until after 2030.

Cold Spray Repairs

There are two applications for cold spray repairs of corroded parts, one with interim approval (Intermediate Gear Support or IGS) and a second application (Static Mast) moving toward interim approval.

- The IGS is a large circular ring inside the AH-64 transmission upon which the Intermediate Gear rests. It is subject to fretting and corrosion. After the corroded part arrives at the CCAD depot, stress testing and analysis are conducted to determine if the part has sufficient remaining strength to build back to original dimensions using cold spray depositions of Al 6061 unto Mg ZE41 substrate.

- The Static Mast is a support system that wraps around the rotor shaft, holds up the rotor head above the transmission and supports rotor bending and control loads. Once approved, it could be the first structural application for cost spray repairs. To repair mechanical damage and corrosion damage, powdered nickel is sprayed unto the 4340 steel substrate.

Opportunities for Costs Savings

For the IGS, when fretting and corrosion damage exceed the damage allowance, cold spray repairs are used to avoid replacing magnesium casting. In an average year, 12 units are replaced at a cost of $18,365 each. Cold spray repairs cost $2,000 per unit.

For the Static Mast, when mechanical and corrosion damage exceed the damage allowance, cold spray repairs will be used to avoid the replacement of the static mast assembly. In an average year, 31 units are replaced at a cost of $36,643 each. Cold spray repairs cost $7,500 per unit.

Depot Backlogs and Aircraft Availability

The replacement of IGS magnesium castings requires substantial lead times of up to 12 months. For the Static Mast, acquisition lead times can range up to 24 months. In contrast, cold spray repairs can be completed in a matter of days or weeks and can eliminate replacement lead times as a contributor to depot level delays and backlogs.

H-1 Super Cobra Attack Helicopter

The Bell Super Cobra is a twin engine attack helicopter used by the Marine Corps. It uses General Electric T700-GE-401C turboshaft engines. They are expected to remain in fleet service until 2033.

Chaffing Damage to the H-1 Combining Gear Box

The combining gear box is a large magnesium casting common to three variants of the H-1 rotorcraft, Whisky, Zulu, and Yankee. The oldest variant (type W) has 125 aircraft and will be phased out by 2021. The Zulu variant (type Z) is currently at 40 aircraft to be build up to 175. The newest Yankee variant (type Y) is currently at 108 aircraft to build up to 150. Zulu and Yankee at 175 and 150 respectively will meet Marine Corps total requirements for 325 aircraft.

In normal use, the combining gear box suffers external chaffing damage to the magnesium housing. Without an acceptable repair technology, once the chaffing damage exceeds the damage allowance, the magnesium housing is replaced

Chafing damage is observed on the older Whisky variant and also on the newer Zulu and Yankee variants. Due to higher stress locations on the newer variants, the rate of chaffing appears to be even more aggressive than for the older Whisky variant. As the fleet transitions to the newer Z and Y variants, cold spray repairs will continue to provide cost savings and depot level operational benefits, possibly at higher than current rates.

Scheduled and Unscheduled Gearbox Rebuild

- When combining gear boxes are rebuilt as part of scheduled in-depot overhaul, on average 20 gearboxes are replaced each year.

- If excessive chaffing damage is detected in the field, the gearbox is removed from the aircraft and returned to the OEM (Bell Helicopter) for an unscheduled rebuild. The OEM disassembles the gearbox, replaces the damaged Mg casting, reassembles and qualifies the rebuilt gear box and returns it to field. For unscheduled repairs, eight gear boxes are rebuilt each year with new magnesium castings.

Opportunities for Costs Savings

During scheduled in-depot overhauls the replacement cost of combined gearbox Mg castings is $265,700 per unit. Cost spray cost is $3,000 per unit.

For unscheduled rebuilds, the replacement cost per unit is $578,000, composed of the cost of the Mg casting ($265,700 per unit) and transportation and OEM labor costs ($312,300 per unit). Cold spray costs are $3,000 per unit.

Depot Backlogs and Aircraft Availability

While the replacement of magnesium castings requires substantial lead times of up to 12 months, there are up to 40 currently condemned H-1 combining gear boxes in FRC-E storage. These gearboxes can be refurbished using cold spray repairs at a fraction of their full replacement cost. The combined effect of a large inventory of refurbished spares together with the rapid repairs of incoming combining gear boxes, will significantly improve depot level throughput, reduce aircraft downtimes and increase the operational readiness of U.S. Marine Corps aviation assets.

Cold Spray Capacity Utilization

Repairing 28 gearboxes per year (8 unscheduled and 20 scheduled) is expected to require up to 10% capacity of the two low pressure cold spray systems at FRC-E and at Camp Pendleton. The remaining 90% of available capacity can support cold spray repairs for additional future NAVAIR applications, as they are developed and approved over time.

<u>T-700 Engine</u>

The General Electric T700-GE-401C turboshaft engine is common across the UH-60, AH-64 and H-1 aviation platforms

Cold Spray Repairs

The T-700 Front Frame Housing sits at the front of the engine. It is made from C355 aluminum alloy. The inlet guide vane spindle contacts the front frame housing, inducing corrosion and wear to the mating surface

Opportunities for Costs Savings

Without cold spray repairs, 24 Front Frame Housings are decommissioned each year. The replacement cost is $13,507 per unit and cold spray costs are $3,000 per unit.

F-18 Super Hornet

The Boeing F -18 Super Hornet is a twin engine, carrier-capable multirole fighter aircraft, expected to remain in Fleet service until after 2035.

Cold Spray Repairs

There are 3 approved applications for the Airframe Mounted Accessory Drive (AMAD)

- Main Housing - Hydraulic Pad restoration. Aluminum is sprayed on aluminum substrate
- Main Housing - Gear failure repair. Interior damage to aluminum casting is caused by gear spin-out. Dimensional restoration is achieved with spraying aluminum powder on aluminum substrate.
- Hydraulic Gear Shaft - Seal surface repair. Stainless steel powder is sprayed on stainless steel substrate.

Opportunities for Costs Savings

Without cold spray repairs, AMAD main housing corrosion damage or interior damage caused by gear failure would result in the housing being decommissioned. In an average year, 20 units are replaced due to hydraulic pad corrosion and 11 units due to gear failure. Average cost to replace the main housing is estimated at $125,000 per unit, composed of $25,000 for the part and $100,000 for labor associated with replacing the part. Cold spray costs are $10,000 per housing.

Without cold spray repairs, the AMAD Hydraulic Gear Shaft Seal would be scrapped. On an annual basis the number of units is estimated at 120. Replacement cost is $10,000 per unit. Cold spray cost is $5,000 per unit.

Depot Backlogs and Aircraft Availability

The replacement of AMAD Main Housing requires substantial lead times of up to 18 months. In contrast, cold spray repairs can be completed in a matter of weeks and can eliminate replacement lead times as a major contributor to depot level delays and backlogs.

B1-B Lancer

The Boeing B-1 Lancer is a four-engine supersonic, heavy strategic bomber used by the United States Air Force. The B1-B fleet has been deployed nearly continuously since 2001, logging approximately 9000 combat hours per year. It is, expected to remain in service until after 2040.

Cold Spray Repairs

B1-B program office approved two cold spray applications:

- Repair of forward equipment Bay (FEB) panels for chafing wear. Dimensional restoration is achieved by spraying aluminum 6061 on aluminum 2024 substrate.
- Deposition of sacrificial layer unto hydraulic lines to reduce chafing point wear in the main landing gear well and in the nose landing gear well. Titanium 32-5 is sprayed unto CP-Ti substrate.

FEB Panel Damage Mechanisms & Opportunities for Cost Savings

FEB panels are large (3 foot by 4 foot) highly curved surfaces close to the nose of the supersonic B1-B aircraft. On each side of the airplane, there are four FEB panels - two upper and two lower panels. FEB panels experience high flight loads.

One edge of the panel is attached to the aircraft with hinges. The other three sides are attached with steel fasteners through holes around the edges of the aluminum panel. FEB panels provide access to avionics and radar equipment and are frequently removed to inspect these critical systems. As steel fasteners are reattached, under considerable torque, the aluminum surface of the countersunk area experiences wear over time. High aerodynamic loads are an additional source of chafing wear around countersunk holes in the aluminum skin.

Upper FEB panels are more prone to wear damage and, without cold spray repairs, 36 panels are replaced each year. For lower panels, the annual replacement rate is 24. Average cost to replace upper FEB panels is $117,000 per unit. Average cost to replace lower FEB panels is estimated at $52,200. The cost of cold spray repairs is $15,000 per unit. Since 2012, several B1-B aircraft have been flying with FEB panels that have been repaired with cold spray.

Hydraulic Tube Damage Mechanisms & Opportunities for Cost Savings

Hydraulic tube chafing in the B 1-B wheel wells is an important driver for non-mission capable (NMC) status. Statistically, excessive wear of hydraulic tubes generates 5,565 hours of unscheduled maintenance during which time aircrafts are NMC.

Hydraulic tubes are wrapped in anti-chafing material to prevent wear. During high tempo operations in desert environments, the wrap slowly collects sand. When airplane engines are running, the hydraulic tubes vibrate at high rates and sand in the wrap gradually vibrates through the hydraulic tubes creating a hole in the line leading to possible loss of hydraulic fluid

During the 2006 to 2011 period, it is reported that hydraulic tube chafing led to tube failures on thirteen B1-B aircraft. Other B1-B aircraft also suffered chafing wear exceeding allowable limits and required the unscheduled replacement of hydraulic lines.

An unpublished 2012 study, conducted at the Oklahoma City Air Logistics Center (OC-ALC) and the 28th Bomb Wing at Ellsworth AF, identified hydraulic tube chafing as one of the most significant maintenance problems for the B1-B fleet due to the

- Difficulty of cutting and bending replacement hydraulic tubes to match the unique contours of individual aircraft (Hydraulic tubes are custom built for each aircraft) and
- Associated cavitation of the hydro system causing other failures (pumps, valves, etc.)..

To reduce the frequency and severity of chafing damage, supersonic cold spray can be used to deposit a titanium coating on titanium hydraulic tubes to provide a sacrificial wear surface in areas of known chafing problems. This preventative measure can be performed during programmed depot maintenance or in field maintenance facilities (with portable CS systems).

In 2011, titanium was cold sprayed unto CP-Ti hydraulic tubes on two B1-B aircraft, which have since logged over 4000 hours without reported problems.

The 2012 unpublished study (above) used a simulation model to identify possible cost savings from cold sprayed sacrificial layers on hydraulic tubes. In general, these savings are realized from an estimated 30% reduction in the number of unscheduled chafing repair incidents and from reduced maintenance costs per incident. Simulation results indicated over $5 million of potential annual savings from (1) reduced incidents of unscheduled maintenance actions in between depot cycles and (2) reduced maintenance hours per incident.

Given that the simulation model used a very high ($1,000 per hour) maintenance labor rate, annual savings for the current benefit cost analysis, were reduced 80% (or by 4/5ths) from simulation model cost savings of over $5million to cost savings of $1,103,910 per year.

The rationale for this adjustment is a recognition that the $1,000 hourly rate consists of a variable labor component of no more than $200 per hour and a fixed component of $800 representing sunk costs for facility and equipment. When cold spraying of hydraulic tubes is implemented across the B1-B fleet, variable cost savings at the rate of $200 per hour may be achieved, while sunk costs of $800 per hour are unlikely to go away.

Longer Term Opportunities with Significant Potential

Additional opportunities for cold spray utilization, which have not yet progressed toward a formal approval, also have high potential for generating DOD benefits. These include:

- F-15 AMAD Wear Sites
- F-16 Air Inlet Housing
- F-16 ADG – Accessory Drive Gearbox
- JSF Magnesium gearboxes
- B-1 Bomber – Additional inspection panels (beyond the 8 FEB panels per aircraft)
- Periscope repair – U.S. Navy SSN and SSBN submarines
- Structural Repairs for Transmission Gearboxes for UH-60, AH-64, SH-60, CH-53, CH-47, H-1Y, and H-1Z aircraft

- Structural Repairs for Main Gearbox for UH-60, AH-64, CH-53, CH-47, F-16, etc.
- Army ground vehicles – Surface repairs and EMI shielding

SECTION 5: BENEFITS FROM COLD SPRAY REPAIRS

Environmental Benefits

Cold spray can be used to reduce environmental damage associated with primary production of magnesium and the utilization of chromated surface treatments.

Primary Production of Magnesium

With cold spray repairs, it is possible to avoid the replacement of magnesium components with new components made from primary magnesium.

- For each ton of primary production (from MgO ores), 17.8 tons of carbon equivalents are generated
- The mining, refining, and recycling of rare earth elements (which are added to magnesium alloys to make them stronger) also have significant environmental consequences, if not properly managed. One hazard is radioactive slurry tailings from the common occurrence of thorium and uranium in rare earth ores. Another is the use of, toxic acids in the refining process. These environmental risks can be reduces when cold spray repairs are used to avoid the replacement of magnesium castings and housings.

Chrome Reduction

Magnesium is an electrochemically active metal and must be protected against galvanic corrosion when coupled with other metals in the presence of an electrolyte.

To protect sealing or mating surfaces, the standard practice is to hard anodize the surface with chromated Dow 17 or use a chromated conversion coating, followed by a sealant compound. To protect non-sealing surfaces, the standard practice is to hard anodize the surface with Dow 17, seal with Rockhard and finish with a chromated primer and topcoat.

It has been demonstrated that cold spray can be used for dimensional restoration <u>without</u> the standard practice of chromated surface treatments.

- For the UH-60 program, a new surface treatment is being introduced for non-structural applications
- Mg parts and corroded areas repaired with cold spray will be an anodized with non-chromated TAGNITE.
- However, for non-sealing surfaces, the anodized layer will continue being covered with a chromated primer and topcoat.

There may be an opportunity to migrate away from chromated primers in the near future. Several respondents from aviation program offices referenced an ongoing ESTCP project (WP-201132) to validate the operational performance of non-chromated primers. Respondents continue to monitor this ESTCP funded effort and may be able to implement non-chromated primers that are successfully validated.

Cost Savings

The analysis of cost savings is presented in three parts.

- Annual cost savings from cold spray repairs and cold spray depositions are estimated for thirteen approved applications and two applications moving toward approval.
- Base-case cost savings are projected over the remaining service life of the aviation assets and other platforms for which cold spray repairs have been approved or are moving toward approval. Base-case cost savings from these 15 applications are aggregated into a combined time series which is used to generate performance metrics (net present value and benefit cost ratio).
- Two additional scenarios are presented, one more optimistic than the base-case and one more conservative than the base-case. Performance metrics for these two additional scenarios are generated and compared to base-case performance metrics.

Base-Case Annual Cost Savings

A flowchart for estimating annual cost savings is presented in Figure 4. To arrive at cost saving per unit, the cost of cold spray repairs is subtracted from the replacement cost of the condemned unit. It is multiplied by the average annual number of condemned units to yield annual cost savings for each repair application. To reflect the inherent implementation uncertainties of new technologies, estimated annual cost savings are multiplied by the probability of realizing these cost savings. The product of this last step is the expected value (EV) of cost savings for each application. Probability estimates reflect discussions with Army and Air Force program offices and with NAVAIR and NAVSEA engineering staff.

Figure 4: Approach for Estimating the Expected Value of Annual Cost Savings

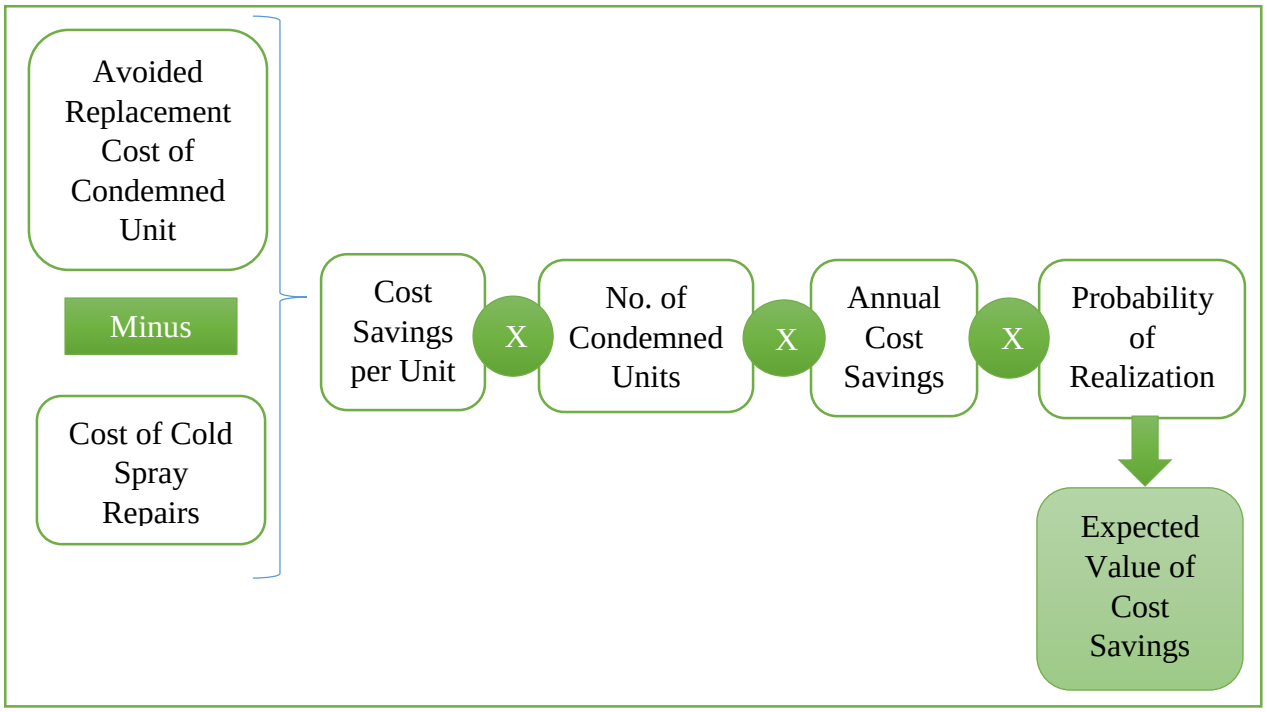


Table 5: Annual Cost Savings ($ Thousand) for Base Case Scenario

	Avoided Replace Cost per Unit	Cold Spray Cost per Unit	Cost Savings per Unit	Annual Replace Rate	Annual Cost Savings	Prob. Realiza -tion	EV of Annual Cost Savings
	Units	$K	$K	Units	$K	%	$K
APPROVED APPLICATIONS							
H-1 Comb Gearbox							
Scheduled Repair	265.7	3	262.7	20	5,254	85	4,466
Unscheduled Rep.	578	3	575	8	4,600	85	3,910
B1-B FEB Panels							
Upper Panel	117	15	102	36	3,672	85	3,121
Lower Panel	52.2	15	37.2	24	893	85	759
UH-60							
Sump	14.4	2	12.4	2	25	85	21
IGB	36.2	5	31.3	25	782	85	665
Tail Rot GB	72.3	3.5	68.8	16.3	1,122	85	954
ADG	35.4	3	32.4	4.5	146	85	124
Input Module	84.4	5	79.4	5	397	85	337
F-18 AMAD							
Hydraul Pad	125	10	115	20	2,300	85	1,955
Gear Failure	125	10	115	11	1,265	85	1,075
Shaft Seal	10	5	5	120	600	85	510
AH-64 IGB Support	18.4	2	16.4	12	196	85	167
T700 Front Frame	13.5	3	10.5	24	252	85	214
B1-B Hydro Tube					1,104	85	938
Total - Approved					22,608		19,216
PROGRESSING TOWARD APPROVAL							
AH-64 Static Mast	36.6	7.5	29.1	31	903	65	587
TD-63 Actuator	20	5	15	4.5	68	65	44
Total					971		631
TOTAL					23,579		19,848

As an example of expected value estimation (following the flowchart in Figure 4), the replacement cost of the H-1 magnesium combining gearbox when scheduled as an in-depot overhaul, is $265,700. To repair the gearbox with cold spray is estimated at $3,000 per unit, for a net cost savings of $262,700 per gear box. The average number of gearboxes which are condemned each year, in the absence of cold spray repairs, is 20 units. With an 85% probability of realization, the expected value of annual cost savings is $4,466,000.

Cost savings from cold spray depositions on B1-B hydraulic tubes are a special case and were estimated via simulation model conducted at the Oklahoma City Air Logistics Center (OC-ALC) and the 28th Bomb Wing at Ellsworth AFB. Using cold spray deposition to reduce chafing wear will (according to simulation results) reduce the number of unscheduled chafing incidents in between depot cycles by approximately one third from an average of 90 per year to 60 per year. The reduction in incidents is accompanied by fewer maintenance hours per incident resulting in annual maintenance cost savings of $1,103,910. With an 85% probability of realization, the expected value of annual cost savings is $938,000.

Total annual cost savings for the thirteen approved applications is 22,607,622 and the expected value at an 85% probability is 19,216,479. Annual cost savings for two additional cold spray applications moving toward approval are estimated at $970,933. Given somewhat greater implementation uncertainty for applications that have not yet reached interim approval stage, a 65% probability is used to arrive at the $631,105 expected value of annual cost savings for these two applications.

The expected value of annual cost savings from all 15 applications is $19,847,585. Annual savings and expected values for all applications, approved and moving toward approval, are summarized in Table 5.

Base-Case Cost Saving Projections

Projected cost savings over the remaining service life of DOD aviation assets and of Navy submarines are used to compute performance metrics (Net Present Value and Benefit Cost Ratio) for cost savings over time. Projected cost savings for a base case scenario are summarized in Table 6 and reflect the following assumptions

- A DOD investment of $36.6 million (composed of ARL and ESTCP investments and subsequent investments that were stimulated by early ARL and ESTCP funding) are deemed to have occurred at a midpoint of 2012.
- For approved applications, cost savings are assumed to ramp up to full annual utilization over a period of two years. In 2016 cost savings are assumed to be at 50% of full utilization. In 2017, cost savings are assumed to reach full annual utilization.
- For the two applications that are still progressing toward interim approvals, it is assumed that the beginning of cost savings is delayed until 2018. From that point onward, cost savings are assumed to ramp up to full annual utilization rates over a period of two years reaching full annual utilization by the end of 2019.

For purposes of analysis, aviation asserts and submarine platforms, for which cold spray repairs are used, are expected to be retired from active service in

- 2030 for the UH-60 and AH-64
- 2033 for the H-1 helicopter and T-700 engine
- 2035 for the FA-18 and
- 2040 for B1-B and Navy submarines

Table 6 entries reflect the above assumptions about the timing of federal investments, the timing and ramp-up of cold spray cost savings, and the remaining service lives of military assets. Table 6 presents an abridged version of the cost savings over the 2012 to 2040 period. For the full version, see spreadsheets in Appendix C.

As an example of projected cost savings (Table 6), cold spray repairs to the magnesium combining gearbox on the H-1, reach 50% of full utilization rates in 2016 and generate savings of $2,233,000. By 2017, full utilization rate is reached and savings are $4,466,000. From 2017 through 2033, annual cost savings continue at $4,466,000 in 2015 dollars. After 2033, the H-1is assumed to have reached the end of its service life and cost savings form cold spray applications are discontinued.

As another example from Table 6, cold spray repairs to the AH-64 Static Mast are not yet approved. However, they are progressing toward approval and cost savings are assumed to start in 2018 at $294,000 and reach full utilization rates and cost savings of $587,000 in 2019. From 2019 through 2030, annual cost savings continue at $587,000. After 2030, the AH-64 is assumed to have reached the end of its service life and cost savings form cold spray applications are discontinued.

Key cost saving amounts and dates in the abridged time series (Table 6) highlights DOD investments and cost savings as follows

- 2012 - Negative $36,600,000 (DOD investments)
- 2016 - First year of approved applications ramping up to $9,609,000 in cost savings
- 2017 - Second year of approved applications ramping up to $19,216,000 in cost savings
- 2018 - First year for “not yet approved” applications ramping up – total savings $19,532,000
- 2019 through 2030 - $19,848,000 of cost savings per year
- 2030 - UH-60 and AH-64 applications drop off
- 2031 through 2033 - $16,933,000 of cost savings per year
- 2033 - H-1 and T-700 applications drop off
- 2034 and 2035 - $8,403,000 in cost savings per year
- 2035 - F-18 applications drop off
- 2036 through 2030 – remaining cost savings of $4,862,000 per year.

See spreadsheets in Appendix C for full presentation of cost savings over 2012-2040 period.

Table 6: Projected EV of Annual Cost Savings ($ Thousand) for Base-Case Scenario

	2012	-	2016	2017	2018	2019	2030	2033	2035	2040
APPROVED APPLICATIONS										
H-1										
Sched			2,233	4,466	4,466	4,466	4,466	4,466		
Unsch			1,955	3,910	3,910	3,910	3,910	3,910		
B1-FEB										
Upper			1,561	3,121	3,121	3,121	3,121	3,121	3,121	3,121
Lower			379	759	759	759	759	759	759	759
UH-60										
Sump			11	21	21	21	21			
IGB			332	665	665	665	665			
TailGB			477	954	954	954	954			
ADG			62	124	124	124	124			
IM			169	337	337	337	337			
F-18										
H Pad			978	1,955	1,955	1,955	1,955	1,955	1,955	
Gear F			537	1,075	1,075	1,075	1,075	1,075	1,075	
Shaft			255	510	510	510	510	510	510	
AH-64 IGB			84	167	167	167	167			
T700			107	214	214	214	214	214		
B1-Hyd			469	938	938	938	938	938	938	938
Total			9,608	19,216	19,216	19,216	19,216	16,948	8,359	4,818
APPLICATIONS MOVING TOWARD APPROVAL										
AH-64 SM					294	587	587			
TD-63					22	44	44	44	44	44
Total					316	631	631	44	44	44
TOTAL	-36000		9,608	19,216	19,532	19,848	19,848	16,993	8,403	4,862

The above time series of investments and cost savings are used to compute the NPV and Benefit Cost Ratio performance metrics. NPV is the net present value of the time series, calculated by the formula:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_o$$

C_t = net cash inflow during the period (positive cost savings)
C_o= initial investment (-36,600,000)
r = discount rate (OMB Circular A-94 real interest rate of 1.3% for maturities of 20 to 30 years)
t = number of time periods (28 years)

Present Value or PV of the time series of cost savings is the NPV plus the investment.

Performance metrics for the base-case scenario are

- NPV of $289.6 million
- PV of $326.2 million ($289.6 million + $36.6 million)

Benefit-to-cost (B:C) ratio = present value of cost savings / investment

- B:C ratio = $326.2 million / $36.6 million = 8.9
- For each dollar of Cold Spray investment, the DOD can expect $9 in cost savings.

Alternative Scenarios

Taking a more conservative approach, the probabilities of realization are reduced to 75% for approved applications and to 50% for applications progressing toward approval.

Taking a more optimistic approach, the probabilities of realization are increased to 90% for approved applications and to 70% for applications progressing toward approval. In addition, to reflect an expected reduction in the cost of a new technology over time, the cost of cold spray repairs is reduced to 75% of base-case costs.

Table 7: Comparison of NPV and Benefit Cost Ratios - Three Scenarios

	Conservative Scenario	Base-Case Scenario	Optimistic Scenario
NPV ($ millions)	250.4	289.6	318.2
B:C	7.8 to 1	8.9 to 1	9.7 to 1

Comparing performance metrics associated with alternative scenarios (Table 7) points to robust cost savings which remain substantial as the probabilities of realizing cost savings change from 75% for approved applications (under the conservative scenario) to 90% under a more optimistic scenario.

- The NPV of cost savings, resulting from the $36,600,000 DOD investment, ranges between $250 million and $318 million
- Benefit Cost ratios point to cost savings of $7.8 to $9.7 for every dollar of DOD investment.

Operational Readiness Benefits

Cold spray repairs will reduce depot level backlogs and non-mission capable (NMC) aircraft. These operational readiness benefits are not included in calculations of cost savings. They represent an effective solution to a major DOD sustainment problem and will have a positive impact on DOD training and combat mission capabilities.

Due to magnesium's high strength to weight ratio, many flight critical components on DOD aviation assets are fabricated from magnesium. Over 4500 helicopters in the DOD fleet have multiple Mg gearboxes which are highly susceptible to corrosion and fretting wear.

Other flight critical parts in DOD aviation assets are made from aluminum, stainless steel and titanium and are also susceptible to excessive chafing wear, etc.

Corroded and worn gearboxes and housings often cannot be repaired and when components exceed corrosion and wear allowances they are decommissioned and replaced.

If spare parts in storage are insufficient to meet replacement needs, long lead times for the procurement of new Mg components can ground aircraft and reduce the operational readiness of the Force. Sometimes, parts can be cannibalized from aviation assets in "boneyards". However that is a limited source of supply and insufficient to cover many replacement needs.

In summary, effective repairs for magnesium, aluminum and other mission critical components are a major sustainment problem for DOD. The dimensions of this problem include

- For regular in-depot overhauls, expensive and long lead time replacement of components,
- For unscheduled replacement of high value components, even greater replacement costs and longer replacement lead times and
- Major supply chain limitations. As an example, there is only one U.S. company (Magnesium Electron Corp.) qualified by Sikorsky Aircraft Co. to manufacture magnesium castings for the UH-60 and AH-64 fleet.

Some examples of sustainment problems, on a Service by Service basis, include

- The U.S. Army's availability target for the UH-60 fleet of 2136 aircraft is 90%, such that no more than 214 aircraft should be non-mission capable at any one time. However up to 20% or over 400 aircraft can be in an NMC status and parts replacement lead times can range up to 12 months
- The Navy identified magnesium component repair and spare parts shortages as one of its top 10 critical technology needs. Reportedly, F-18 aircraft can sit for up to 18 months or more, waiting for replacement parts. If spares are unavailable, Marine Corps H-1 helicopters can wait up to 3 years.
- The Air Force reports that one of the top driver's for B1-B non-mission capable rates are wheel well hydraulic tube chafing which has resulted in 29 hydraulic line chafing failures on 12 aircraft over the 2006 to 2011 period. This problem persists.

DOD views the replacement of corroded and worn gearboxes and housings on its aviation assets as a major sustainment problem which can lead to critical safety and readiness issues.

The cold spray repair technology provides a practical solution to this major sustainment problem. It can be implemented rapidly and cost effectively during in-depot overhaul cycles as well as at field installations and can contribute to

- Fewer condemnations of flight critical components
- Reduced depot level backlogs and costs
- Reduced NMC aircraft and higher on-wing time
- Significantly enhanced operational readiness and
- Enhanced mission capability for DOD aviation assets

Cold spray repairs can also be used to refurbish condemned parts stored at CCAD, FRC-E and other DOD depots and create a spare parts inventory buffer against long lead time procurements for unscheduled repairs.

Parts on aviation assets that are no longer in production are particularly prone to long lead time replacement cycles. For these parts, cold spray repairs and a larger numbers of spares can be used to effectively expand the operational life of aviation assets beyond their original service lives.

The overall impact of cold spray repairs will be to significantly increase the availability of DOD aviation assets for training and combat operations

CONCLUSIONS

Magnesium gearboxes and housings on DOD aviation assets experience significant corrosion and wear problems. Traditional repair methods are generally ineffective and high value gearboxes and housing are often decommissioned and replaced at considerable cost and with long lead times. The results is higher than acceptable non-mission capable (NMC) rates and represents a major DOD sustainment problem.

Over the last decade, the cold spray repair technology was developed and introduced as a cost effective solution to this major sustainment problem and is currently being implemented across Army, Navy and Air Force maintenance depots.

Early in its development (over the 2005 to 2011 period), technology development was supported by an ESTCP investment in the qualification, validation and demonstration of cold spray for magnesium aerospace components. Results from the ESTCP funded project opened the door for subsequent DOD investments to (1) expand applications beyond magnesium components to parts made from aluminum, stainless steel and titanium and to (2) support the implementation of cold spray repairs across the DOD.

Benefits from the development and implementation of the cold spray technology include:

- Reduced environmental damage from avoided primary production of magnesium ingots. Also, reduced utilization of hard anodized chromated surface treatments to protect multi-metal gearboxes and housings from galvanic corrosion.

- Substantial cost savings from avoiding the replacement of high value and long lead-time components. Annual cost savings are expected to exceed $23 million and the benefit to cost ratio - over the remaining service lives of DOD assets with cold sprayed repairs -is expected to be 9:1 for a base case scenario. Accordingly, DOD can expect $9 of cost savings for every dollar invested in the development, validation and implementation of the cold spray technology.

Cold spray repairs also provide a practical solution to a major DOD sustainment problem for its aviation and submarine platforms. With cold spray repairs, the replacement of long lead time components can be avoided, leading to fewer non-mission capable aircraft and higher ” on wing time” performance. The expected outcome will be (1) enhanced operational readiness and (2) increased mission capability for training and combat missions.

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APPENDIX A: LIST OF SUBJECT MATTER EXPERTS

Victor K. Champagne, Jr. Director, ARL Center for Cold Spray US Army Research Laboratory, ATTN: RDRL-WMM-D, BLDG 4600 Aberdeen Proving Ground, MD

Kevin Conner H-1 Senior Drive Systems Engineer
AIR 4.4.2.4 ISE Technical Expert

Tosh Farr Aerospace Systems Engineer
Mechanical Systems F-16 System Program Office

William C. Harris, Innovations Lead
Sikorsky Aircraft Corporation UH-60, CH-53, H-60

Rob Hrabe, President
H. F. Webster Engineering Services, Webster MA

Robert Kestler (Yogi), Science & Technology Lead (AIR-4.0)
Fleet Readiness Center East, ONR Office of Research and Technology Applications Rep.

Frederick Lancaster AIR 4.3.4 Science & Technology Lead (NPRE Air Vehicle Proj PM, NAVAL Air Systems Command Materials Engineering Division, Patuxent River, MD

Dr. Keith Legg, President
Rowan Technology Group, Libertyville, IL

Ricky McNallay
Aviation Engineering Directorate (AED), AMRDEC, Redstone Arsenal, AL

Fernando R. Merritt
Utility Helicopter Program Office, USARMY PEO AVN (US), Redstone Arsenal, AL

Dr. Dick Nadolink (Ret.),
NUWC (Naval Undersea Warfare Center) Division Newport, RI

Aaron Nardi
United Technologies Research Center, East Hartford CT

Mike Nicholas
Boeing, AH-64 Apache Component Engineering, Mesa AZ

Allen F. Poole
CIV USARMY PEO AVN (US) Redstone Arsenal, AL

William J. Raphael,
B-1B Chief Engineer, Structures Engineering Sect. B-1 System Program Office
AFLCMC/WWNLD Tinker AFB OK

Thomas Stamey
Code 260, PSNS & IMF (Puget Sound Naval Shipyard – Intermediate Maintenance Facility)

Don Szczur, USI Inc. Conractor, Army ManTech Cost Analysis

Scott W. Wilson
U.S. Army Utility Helicopters Project Office (UHPO) /CGI Federal SFAE-AV-UH
Redstone Arsenal, AL

APPENDIX B:

ACHIEVEMENT AWARDS FOR ARL CENTER FOR COLD SPRAY

2014 Defense Standardization Program Achievement Awards

Document is displayed on the next page

2012 Defense Standardization Program Achievement Awards

Presented to members of the Cold Spray Team for ESTCP Program 06-E-PP3-031 "Supersonic Particle Deposition Technology for Repair of Magnesium Aircraft Components"

2008 Defense Standardization Program Achievement Award

An Army Research Laboratory technical team was recognized by the Defense Department on March 12, 2009, for its role in the development of the specification, MIL-STD-3021, a Manufacturing Process Standard, entitled: Materials Deposition, Cold Spray. The 2008 Defense Standardization Program (DSP) Achievement Award was presented to the ARL team by DoD's Standardization Program Office. The DSP mission is to identify, influence, develop, manage, and provide access to standardization processes, products, and services for warfighters and the acquisition and logistics communities. In addition, the program promotes interoperability, and assists in reducing total ownership cost and in sustaining readiness.

2007 Defense Manufacturing Excellence Award

The National Center for Manufacturing Sciences (NCMS) managed a cross-industry collaborative team that developed the use of cold spray for corrosion control. The methods developed will impact Department of Defense by significantly reducing corrosion related maintenance across all military services. The NCMS team was recognized by a "Defense Manufacturing Excellence Award" presented by the National Center for Advanced Technologies (NCAT) on December 5, 2007 in Las Vegas, Nevada. The project participants included all the branches of the armed services: The Army ARL, Navy, Air Force and Marines, and the cross-industry companies: The Boeing Company, Delphi Corporation, Ford Motor Company, CenterLine Ltd. and Solidica.

DEPARTMENT OF DEFENSE
DEFENSE STANDARDIZATION PROGRAM OFFICE
8725 JOHN J. KINGMAN ROAD, STOP 5100
FORT BELVOIR, VA 22060-6220

IN REPLY REFER TO DSPO

FEB 23 2015

MEMORANDUM FOR DEFENSE STANDARDIZATION EXECUTIVES

SUBJECT: 2014 Defense Standardization Program (DSP) Achievement Awards

I am pleased to announce the winners of the 2014 DSP Outstanding Achievement Awards. You may notify winners and their nominators as you see fit. We will not contact the winners regarding the ceremony until March 4, 2015, in order to give you time to notify them first. The 2014 winners are:

- **Department of the Army, Aluminum-Based Powders for Cold Spray Deposition Team.** The point of contact is Mr. Richard Squillacioti, RDRL-WMM-D, 4600 Deer Creek Loop, Aberdeen Proving Ground, MD 21005-5069. He can be reached at 410-306-0786 or via email at Richard.j.squillacioti.civ@mail.mil.

- **Department of the Army, Utilization of Biobased Materials for DoD Qualified Cleaner, Lubricant, and Preservative (CLP) for Weapon and Weapon Systems Team.** The point of contact is Mr. Mark Napolitano, RDAR-EIQ-SE, Bldg 92, Picatinny Arsenal, NJ 07806. He can be reached at 973-724-3615 or via email at mark.a.napolitano.civ@mail.mil.

- **Department of the Navy, Advanced Explosive Ordnance Disposal Robotic System (AEODRS) Team.** The point of contact is Mr. Scott Steward, 2008 Stump Neck Road, Indian Head, MD 20640. He can be reached at 301-744-5142 or via email at scott.steward@navy.mil.

- **Department of the Air Force, MIL-DTL -25959 Tie Down, Tensioners Cargo, Aircraft Team.** The point of contact is Mr. Michael C. Jones, 235 Byron St. Suite 19A, Robins AFB, GA 31098. He can be reached at 478-222-1671 or via email at michael.jones.175@us.af.mil.

- **Department of the Air Force, MIL-STD-1791A, Design for Internal Aerial Delivery in Fixed Wing Aircraft Team.** The point of contact is Mr. Mark Kuntavanish, 2145 Monahan Way, Wright Patterson AFB OH 45433-7017. He can be reached at 937-255-2330 or via email at mark.kuntavanish@us.af.mil.

- **Defense Logistics Agency, Mr. Muhammad Akbar, Development of a new device Class "Y", a ceramic Non-hermetic package approach to meet all the requirements of Class "S" for use in space.** The point of contact is Mr. Thomas Hess, Defense Supply Center Columbus, DSCC-VAC, P.O. Box 3990 Columbus, OH 43218-3990. He can be reached at 614-692-0547 or via email at Thomas.Hess@dla.mil.

I sincerely appreciate the hard work of your respective staffs in seeking and screening nominations. Our award winners are clearly deserving of recognition.

The awards ceremony is scheduled for March 25, 2015, from 1400-1600, at the Pentagon, Hall of Heroes, You, your DepSO, the winners' commander and immediate family are invited to attend. Mr. Stephen P. Welby, Deputy Assistant Secretary of Defense, Systems Engineering, will be presenting the awards.

Mr. Tim Koczanski of my staff will be in contact with the DepSOs regarding complete attendance lists and other details necessary in order to make this day a memorable event.

I look forward to seeing everyone on March 25th.

GREGORY E. SAUNDERS
DIRECTOR

cc:
DepSOs

APPENDIX C:

COST ANALYSIS SPREADSHEETS

For Base-Case

- Annual Cost Savings
- Projected Cost Savings 2012 to 2040
- Performance Metrics

ANNUAL COST SAVINGS

ANNUAL COST SAVINGS	Replacement	Cold Spray	Cost Savings	Annual	Annual	Probability	EV of Annual
BASELINE ANALYSIS COLD SPRAY	Cost / Unit	Cost / Unit	/ Unit	Replace Rate	Cost Savings	of Realization	Cost Savings
				(Units)			
APPROVED							
H-1 Scheduled Overhaul	265,700	3,000	262,700	20	5,254,000	0.85	4,465,900
H-1 Un-Scheduled Repairs	578,000	3,000	575,000	8	4,600,000	0.85	3,910,000
B1-B FEB Upper Panels	117,000	15,000	102,000	36	3,672,000	0.85	3,121,200
B1-B FEB Lower Panels	52,200	15,000	37,200	24	892,800	0.85	758,880
UH-60 Sump	14,389	2,000	12,389	2	24,778	0.85	21,061
UH-60 IGB	36,285	5,000	31,285	25	782,125	0.85	664,806
UH-60 Tail Rotor GB	72,341	3,500	68,841	16	1,122,108	0.85	953,792
UH-60 Accessory GB	35,355	3,000	32,355	5	145,598	0.85	123,758
UH-60 Input Module	84,351	5,000	79,351	5	396,755	0.85	337,242
F18 AMAD Hyd Pad Repair	125,000	10,000	115,000	20	2,300,000	0.85	1,955,000
F18 AMAD Gear Failure Repair	125,000	10,000	115,000	11	1,265,000	0.85	1,075,250
F18 AMAD Gear Shaft Seal Repair	10,000	5,000	5,000	120	600,000	0.85	510,000
AH-64 IGS	18,365	2,000	16,365	12	196,380	0.85	166,923
T700 Engine Front Frame	13,507	3,000	10,507	24	252,168	0.85	214,343
Hydraulic Line Sacrificial Layer					1,103,910	0.85	938,324
TOTAL					22,607,622	0.85	19,216,479
PROGRESS TO APPROVAL							
AH-64 Static Mast	36,643	7,500	29,143	31	903,433	0.65	587,231
TD-63 Submarine Actuator	20,000	5,000	15,000	5	67,500	0.65	43,875
TOTAL					970,933		631,106
TOTAL APPROVED &							
MOVING TOWARD APPROVAL					23,578,555		19,847,585

PROJECTED COST SAVINGS - 2012 to 2040

PROJECTED COST SAVINGS	2012	2013	2014	2015	2016	2017	2018	2019	2020
BASELINE ANALYSIS COLD SPRAY									
APPROVED									
H-1 Scheduled Overhaul					2,232,950	4,465,900	4,465,900	4,465,900	4,465,900
H-1 Un-Scheduled Repairs					1,955,000	3,910,000	3,910,000	3,910,000	3,910,000
B1-B FEB Upper Panels					1,560,600	3,121,200	3,121,200	3,121,200	3,121,200
B1-B FEB Lower Panels					379,440	758,880	758,880	758,880	758,880
UH-60 Sump					10,531	21,061	21,061	21,061	21,061
UH-60 IGB					332,403	664,806	664,806	664,806	664,806
UH-60 Tail Rotor GB					476,896	953,792	953,792	953,792	953,792
UH-60 Accessory GB					61,879	123,758	123,758	123,758	123,758
UH-60 Input Module					168,621	337,242	337,242	337,242	337,242
F18 AMAD Hyd Pad Repair					977,500	1,955,000	1,955,000	1,955,000	1,955,000
F18 AMAD Gear Failure Repair					537,625	1,075,250	1,075,250	1,075,250	1,075,250
F18 AMAD Gear Shaft Seal Repair					255,000	510,000	510,000	510,000	510,000
AH-64 IGS					83,462	166,923	166,923	166,923	166,923
T700 Engine Front Frame					107,171	214,343	214,343	214,343	214,343
Hydraulic Line Sacrificial Layer					469,162	938,324	938,324	938,324	938,324
TOTAL					9,608,239	19,216,479	19,216,479	19,216,479	19,216,479
PROGRESS TO APPROVAL									
AH-64 Static Mast							293,616	587,231	587,231
TD-63 Submarine Actuator							21,938	43,875	43,875
TOTAL							315,553	631,106	631,106
TOTAL APPROVED &									
MOVING TOWARD APPROVAL	-36,600,000				9,608,239	19,216,479	19,532,032	19,847,585	19,847,585

PROJECTED COST SAVINGS (Continued)

2,021	2,022	2,023	2,024	2,025	2,026	2,027	2,028	2,029	2,030
4,465,900	4,465,900	4,465,900	4,465,900	4,465,900	4,465,900	4,465,900	4,465,900	4,465,900	4,465,900
3,910,000	3,910,000	3,910,000	3,910,000	3,910,000	3,910,000	3,910,000	3,910,000	3,910,000	3,910,000
3,121,200	3,121,200	3,121,200	3,121,200	3,121,200	3,121,200	3,121,200	3,121,200	3,121,200	3,121,200
758,880	758,880	758,880	758,880	758,880	758,880	758,880	758,880	758,880	758,880
21,061	21,061	21,061	21,061	21,061	21,061	21,061	21,061	21,061	21,061
664,806	664,806	664,806	664,806	664,806	664,806	664,806	664,806	664,806	664,806
953,792	953,792	953,792	953,792	953,792	953,792	953,792	953,792	953,792	953,792
123,758	123,758	123,758	123,758	123,758	123,758	123,758	123,758	123,758	123,758
337,242	337,242	337,242	337,242	337,242	337,242	337,242	337,242	337,242	337,242
1,955,000	1,955,000	1,955,000	1,955,000	1,955,000	1,955,000	1,955,000	1,955,000	1,955,000	1,955,000
1,075,250	1,075,250	1,075,250	1,075,250	1,075,250	1,075,250	1,075,250	1,075,250	1,075,250	1,075,250
510,000	510,000	510,000	510,000	510,000	510,000	510,000	510,000	510,000	510,000
166,923	166,923	166,923	166,923	166,923	166,923	166,923	166,923	166,923	166,923
214,343	214,343	214,343	214,343	214,343	214,343	214,343	214,343	214,343	214,343
938,324	938,324	938,324	938,324	938,324	938,324	938,324	938,324	938,324	938,324
19,216,479	19,216,479	19,216,479	19,216,479	19,216,479	19,216,479	19,216,479	19,216,479	19,216,479	19,216,479
587,231	587,231	587,231	587,231	587,231	587,231	587,231	587,231	587,231	587,231
43,875	43,875	43,875	43,875	43,875	43,875	43,875	43,875	43,875	43,875
631,106	631,106	631,106	631,106	631,106	631,106	631,106	631,106	631,106	631,106
19,847,585	19,847,585	19,847,585	19,847,585	19,847,585	19,847,585	19,847,585	19,847,585	19,847,585	19,847,585

PROJECTED COST SAVINGS (Continued)

2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
4,465,900	4,465,900	4,465,900							
3,910,000	3,910,000	3,910,000							
3,121,200	3,121,200	3,121,200	3,121,200	3,121,200	3,121,200	3,121,200	3,121,200	3,121,200	3,121,200
758,880	758,880	758,880	758,880	758,880	758,880	758,880	758,880	758,880	758,880
1,955,000	1,955,000	1,955,000	1,955,000	1,955,000					
1,075,250	1,075,250	1,075,250	1,075,250	1,075,250					
510,000	510,000	510,000	510,000	510,000					
214,343	214,343	214,343							
938,324	938,324	938,324	938,324	938,324	938,324	938,324	938,324	938,324	938,324
16,948,896	16,948,896	16,948,896	8,358,654	8,358,654	4,818,404	4,818,404	4,818,404	4,818,404	4,818,404
43875	43875	43875	43875	43875	43875	43875	43875	43875	43875
43,875	43,875	43,875	43,875	43,875	43,875	43,875	43,875	43,875	43,875
16,992,771	16,992,771	16,992,771	8,402,529	8,402,529	4,862,279	4,862,279	4,862,279	4,862,279	4,862,279

PERFORMANCE METRICS

	Conservative Scenario	Base-Case Scenario	Optimistic Scenario
Total Cost Savings ($Millions)	333.1	378.6	412
NPV ($Millions)	250.4	289.6	318.2
Investment ($Millions)	36.6	36.6	36.6
Present Value ($Millions)	287	326.2	354.8
Benefit Cost Ratio	7.84 to 1	8.91 to 1	9.69 to 1