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Review of Corrosion Control Programs and Research Activities for Army Vehicles

Land Sustain (12S) Thrust Advisory Group Scoping Study

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Prepared as part of the 12S Army Sustain Thrust Scoping Study on Materials in part response to issues raised by DLR and DSVPM.

Defence R&D Canada – Atlantic

Technical Memorandum

DRDC Atlantic TM 2006-055

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Abstract

The purpose of this report was to provide a critical review of recent developments in corrosion prevention programs for U.S. Army vehicles and to identify related issues from a Canadian perspective. It was prompted by awareness of the rising costs of applying a corrosion preventive compound (CPC) to Canadian Army vehicles. The review was mostly based on the presentations at the latest U.S. Tri-Service Corrosion Conference (November 2005) and the U.S. Army Corrosion Summit (February 2006), which include the recent development of U.S. Army corrosion program and research activities on new coating materials and application techniques, testing coating techniques, corrosion preventive compounds, and corrosion sensors. A comprehensive corrosion control program was also recommended in the report to better mitigate the corrosion cost and to improve the readiness and availability, and to increase the service life of the Canadian Army vehicles.

Résumé

Le présent rapport a comme objectif de fournir un examen critique des progrès récents réalisés dans le cadre de programmes de prévention de la corrosion des véhicules de l’Armée des États-Unis et d’établir quelles sont les questions connexes propres au contexte canadien. L’étude a été entreprise à la suite de la hausse des coûts d’application d’enduits anticorrosion pour traiter les véhicules de l’Armée canadienne. Les données obtenues proviennent en grande partie des présentations effectuées lors de la dernière U.S. Tri-Service Corrosion Conference (novembre 2005) et du U.S. Army Corrosion Summit (février 2006), lesquelles traitaient, entre autres, de l’élaboration de récents programmes et projets de recherche de l’Armée américaine portant sur la corrosion, notamment les nouveaux matériaux de revêtement et les techniques d’application de pointe, les techniques de revêtement, les enduits anticorrosion et les détecteurs de corrosion. Le rapport contient aussi des recommandations sur un programme détaillé de protection contre la corrosion ayant pour but de réduire encore plus les coûts liés à la corrosion et, de ce fait, d’améliorer l’état de préparation et la disponibilité des véhicules de l’Armée canadienne et d’en accroître la durée de vie utile.

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Executive summary

Review of Corrosion Control Programs and Research Activities for Army Vehicles: Land Sustain (12S) Thrust Advisory Group Scoping Study

Yueping Wang, Royale S. Underhill, Bob Klassen; DRDC Atlantic TM 2006-055; Defence R&D Canada – Atlantic; August 2006.

Introduction: The purpose of this report is to provide a critical review of recent developments in corrosion prevention programs for U.S. Army vehicles and to identify related issues from a Canadian perspective. It was prompted by awareness of the rising costs of applying a corrosion preventive compound (CPC) to Canadian Army vehicles. The review is based mostly on the presentations from the latest U.S. Tri-Service Corrosion Conference (November 2005) and the U.S. Army Corrosion Summit (February 2006), which include the recent development of a U.S. Army corrosion program and research activities on new coating materials and application techniques, coating testing techniques, corrosion preventive compounds, and corrosion sensors. The review of the corrosion issues on Canadian Army vehicles was based on the information from DLR 6 and DSVPM 3.

Review of Corrosion Issues on Canadian Army Vehicles: In the fall of 2000, an inspection of Medium Logistics Vehicle Wheeled, the oldest fleet of logistics vehicles, raised safety concerns. After 18 years in service, there was evidence of advanced corrosion and structural damage. A separate inspection indicated that 25% of the fleet suffered from severe corrosion. In 2001, DND initiated a corrosion control and body maintenance program for combat service support vehicles. The program involved the application of Krown T-40, a CPC, to the vehicles. The increasing cost of the corrosion control and body maintenance program and reduced fleet size as a result of corrosion damage have prompted an interest in more proactive corrosion prevention program for the Army vehicles.

Review of U.S. Army Corrosion Program: Following the 2002 U.S. Federal Highway Administration study on corrosion costs and preventive strategies in the United States, U.S. Army initiated a full spectrum national corrosion prevention and control program to resolves corrosion issues. The U.S. army's R&D, test and evaluation programs review and recommend safe and effective corrosion prevention and control technologies. Their goal is on approving commercial off-the-shelf technologies that are suitable for military use and resolving technology gaps through research.

As part of its corrosion control and prevention program, U.S. Marine Corps (USMC) has developed a corrosion management tool for their ground combat and combat support vehicles. The goals of adopting this corrosion management tool are to increase equipment

readiness and availability, reduce negative operational effects (because problems are known and can be solved), and identify the annual corrosion costs requirement. The U.S. Army has shown strong interest in utilizing the USMC corrosion assessment tool to assist in identifying the extent of corrosion and mitigation cost. Advanced storage technologies (dehumidification and equipment covers impregnated with vapour phase corrosion inhibitor) were also adopted as part of corrosion control and prevention program to mitigate corrosion during equipment storage.

Research Activities Relevant to Army vehicles: Significant research activities are on going to develop, test, and evaluate the new coating materials and application technologies that could potentially serve as alternatives to chromate, cadmium, and heavy metal coatings. Some of the new coatings under development include self-healing coatings with corrosion inhibitors carried by nanoparticles or microcapsules and released by the onset of corrosion; electroactive and conductive polymer coatings; active coatings that can alert the logistics staff when corrosion damage occurs; and surface mineralization. Various techniques for testing coating materials were developed, which can be used for various purposes. These techniques can be categorized as long-term exposure tests, accelerated cabinet tests (ASTM standards and automobile industry standards), and electrochemical techniques (electrochemical impedance spectroscopy). Active corrosion/coating sensors are being developed to measure *in situ* corrosion rate and/or coating integrity. Selected review of the testing on CPCs conducted by Defence Science and Technology Organization (DSTO), Australia, Quality Engineering Test Establishment (QETE), and Royal Military College of Canada (RMC) was also presented in the report.

Options/Recommendations: A comprehensive corrosion control program is recommended to minimize the corrosion damage and to increase the equipment readiness, availability and service life of the Canadian Army vehicles. The program should include a corrosion survey, condition-based maintenance, use of advanced storage technologies, and use of new coating repair techniques. For new procurements, the program should ensure that cost-effective new coating materials and coating application technologies be adopted on the new vehicles.

Sommaire

Review of Corrosion Control Programs and Research Activities for Army Vehicles: Land Sustain (12S) Thrust Advisory Group Scoping Study

Yueping Wang, Royale S. Underhill, Bob Klassen; DRDC Atlantic TM 2006-055; R & D pour la défense Canada – Atlantique; août 2006.

Introduction: Le présent rapport a pour objectif de fournir un examen critique des progrès récents réalisés dans le cadre de programmes de prévention de la corrosion des véhicules de l'Armée des États-Unis et d'établir quelles sont les questions connexes propres au contexte canadien. L'étude a été entreprise à la suite de la hausse des coûts d'application d'enduits anticorrosion pour traiter les véhicules de l'Armée canadienne. Les données obtenues proviennent en grande partie des présentations effectuées lors de la dernière U.S. Tri-Service Corrosion Conference (novembre 2005) et du U.S. Army Corrosion Summit (février 2006), lesquelles traitaient, entre autres, de l'élaboration de récents programmes et projets de recherche de l'Armée américaine portant sur la corrosion, notamment les nouveaux matériaux de revêtement et les techniques d'application de pointe, les techniques de revêtement, les enduits anticorrosion et les détecteurs de corrosion. L'examen des questions ayant trait à la corrosion des véhicules de l'Armée canadienne est basé sur les renseignements fournis par la DBRT 6 et la DAPVS 3.

Examen des questions ayant trait à la corrosion des véhicules de l'Armée canadienne: À l'automne de l'an 2000, l'exécution de l'inspection de la plus vieille flotte de véhicules logistiques, celle des véhicules logistiques moyens à roues, a permis de soulever des préoccupations liées à la sûreté de l'ensemble roue. Après 18 années de service, un pourcentage important des ensembles roues de ces véhicules présentaient des signes de corrosion avancée et de dommages structuraux, ce qui se traduit par une importante perte d'intégrité. Les résultats d'une inspection distincte de la flotte indiquaient aussi que 25% des véhicules présentaient de sérieux problèmes de corrosion et que les coûts des réparations dépasseraient la limite de dépense autorisée à ce chapitre, soit 4500$. En 2001, le MDN a lancé un programme de lutte contre la corrosion et d'entretien de la carrosserie de véhicules de soutien logistique du combat. Il comprend, entre autres éléments, l'application de KrownT-40, un enduit anticorrosion, pour traiter les véhicules. Les coûts croissants associés au programme de lutte contre la corrosion et d'entretien des carrosseries, ainsi que la réduction de la taille de la flotte attribuable aux dégâts dus à la corrosion, ont aiguisé l'intérêt pour un programme de prévention de la corrosion des véhicules de l'Armée présentant une approche plus proactive.

Examen du programme de prévention de la corrosion des véhicules de l'Armée des États-Unis et des activités de recherche connexes: L'administration fédérale des autoroutes des États-Unis (U.S. Federal Highway Administration) a exécuté, en 2002, une étude sur les coûts reliés à la corrosion des véhicules et les stratégies de prévention de la corrosion adoptées dans ce pays. Les résultats de l'étude ont incité l'Armée des États-Unis à lancer un programme national global de prévention et de lutte contre la corrosion ayant pour but de résoudre les problèmes de corrosion de ses véhicules. Dans le cadre des différents programmes de R-D, de mise à l'essai et d'évaluation de l'Armée des États-Unis, on a examiné les techniques utilisées dans ce domaine et recommandé l'emploi de celles qui sont les plus efficaces et sécuritaires. Les divers programmes susmentionnés ont pour objectifs l'approbation de techniques commerciales, disponibles sur le marché, qui permettent de répondre adéquatement aux besoins militaires, ainsi que la résolution des écarts technologiques grâce à l'exécution de travaux de recherche.

Dans le cadre de son propre programme de prévention et de lutte contre la corrosion, le Corps des Marines des États-Unis (U.S. Marine Corps ou USMC) a mis au point un outil de gestion de la corrosion pour ses véhicules de combat terrestre et d'appui au combat (voir l'annexeA). L'adoption de cet outil a pour but d'accrotre l'état de préparation et la disponibilité de l'équipement, de réduire les effets négatifs sur les opérations (la nature des problèmes étant clairement établie, leur résolution est plus facile) et de déterminer les besoins en matière de coûts annuels liés aux problèmes de corrosion. L'Armée des États-Unis a montré un vif intérêt pour l'outil d'évaluation de la corrosion de l'USMC, qui peut servir à établir l'importance de la corrosion et des coûts des mesures d'atténuation. De plus, il faut souligner que des techniques d'entreposage de pointe (par exemple, la déshumidification et l'emploi de couvertures de protection de l'équipement imprégnées d'un inhibiteur de corrosion en phase vapeur) sont adoptées, dans le cadre de certains programmes de prévention et de lutte contre la corrosion, afin d'en atténuer les effets lors de l'entreposage de l'équipement.

D'importants travaux de recherche en cours visent à élaborer, mettre à l'essai et évaluer de nouveaux matériaux de revêtement, ainsi que les techniques d'application de pointe, qui pourraient constituer des solutions de remplacement pour les revêtements contenant des chromates, du cadmium et des métaux lourds. Les nouveaux revêtements en cours d'élaboration comprennent des revêtements autorégénérants contenant des inhibiteurs de corrosion, sous forme de nanoparticules ou de microcapsules, qui peuvent être libérés dès la première étape de la corrosion, ainsi que des revêtements à base de polymères électroactifs et conducteurs. Il faut aussi mentionner des revêtements actifs indicateurs qui permettent au personnel chargé de la logistique de détecter les dégâts dus à la corrosion, et finalement, des produits du domaine de la minéralisation de surface. Différentes techniques de mise à l'essai des matériaux de revêtement ont été mises au point, à diverses fins. Elles peuvent être classées parmi les essais d'exposition prolongée, les essais accélérés en enceinte fermée (méthodes normalisées de l'ASTM et normes de l'industrie automobile) et les techniques électrochimiques (par exemple, la spectroscopie d'impédance électrochimique). Des travaux de mise au point portent sur des revêtements actifs détecteurs de corrosion, qui permettent de mesurer insitu la vitesse de corrosion ou l'intégrité du revêtement, ou ces deux caractéristiques. Le rapport contient aussi des données choisies de l'examen des résultats d'essais effectués sur des enduits anticorrosion par des chercheurs d'un organisme de recherche d'Australie, la Defence Science and Technology Organization (DSTO), du Centre d'essais techniques de la qualité (CETQ) et du Collège militaire royal du Canada (CMRC).

Solutions et recommandations: Les recommandations comprennent la mise en œuvre d'un programme détaillé de protection contre la corrosion ayant pour but de réduire au minimum les dégâts dus à la corrosion et, de ce fait, d'améliorer l'état de préparation et la disponibilité des véhicules de l'Armée canadienne et d'en accrotre la durée de vie utile. Parmi les éléments du programme, on devrait compter l'exécution d'une enquête sur la corrosion, l'emploi de mesures de maintenance basées sur l'état des pièces et des véhicules, ainsi que la mise en œuvre de techniques d'entreposage de pointe et de nouvelles techniques de réparation de revêtements. Dans les cas d'acquisition de nouveaux véhicules, le programme devra comprendre certains critères obligatoires qui permettront d'assurer l'adoption et l'emploi de nouveaux matériaux de revêtement et de techniques d'application de revêtements de pointe qui sont rentables.

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1 Introduction

The purpose of this report is to provide a critical review of recent developments in corrosion prevention programs for U.S. army vehicles and to identify related issues from a Canadian perspective. It was prompted by awareness of the rising costs of applying a corrosion preventive compound (CPC) to Canadian Army vehicles. The corrosion related costs for U.S. Army ground vehicles alone are estimated to be $2 billion per year [1]. Answers as to how the U.S. could address corrosion related issues were presented at the 2005 Tri0service corrosion conference [2] and the U.S. Army Corrosion Summit [3].

The U.S. has addressed the issue of corrosion at the political level. By an act of Congress in 2003, the Department of Defense (DoD) designated an organization to oversee corrosion prevention, and mitigation and to direct a long term strategy to reduce corrosion and its effects. As a result of this law, all DoD purchases over ten thousand dollars now require a corrosion control plan before acquisition. In response to the emphasis on corrosion, the DoD Corrosion Exchange website (www.dodcorrosionexchange.org) was established. This site is designed to promote and facilitate interactions between the branches of the U.S. forces, academia and industrial suppliers. There are currently about 1700 members and becoming a member requires filling out a form on-line, receiving a phone call interview and agreeing to not advertise.

In this report, a brief review of the state of Canadian Army vehicles from a corrosion perspective is presented first, followed by a critical review of U.S. Army corrosion program and recent research activities on Army vehicle corrosion control. The recommended actions to minimize the corrosion damage to Canadian Army vehicles are also presented.

2 Canadian Army Vehicles Corrosion Issues

The Canadian Army vehicles can be largely classified as two categories: combat vehicles (“A” Fleet) and combat service support vehicles (“B” Fleet). Although there are corrosion issues in both Fleets, only the ones in “B” Fleet vehicles are identified and discussed in this report.

The “B” Fleet vehicles can be further classified as the following four fleets according to their operational functions:

1. Light Utility Vehicle Wheeled (LUVW)
2. Light Support Vehicle Wheeled (LSVW)
3. Medium Logistic Vehicle Wheeled (MLVW)
4. Heavy Logistic Vehicle Wheeled (HLVW)

There are total 2200 LUVWs, including 1139 standard military pattern (SMP) vehicles (General Motors) and 1061 militarized commercial off-the-shelf (Milcots) vehicles (Daimler Chrysler). Both fleets are the replacements of Iltis. The SMP and Milcots entered in service in 2004 and 2003, respectively. Both fleets came with a full corrosion package for 15 years. No immediate concern on corrosion was reported.

There are approximately 2750 LSVWs, including 1081 cargos and 281 Field Office and Command post vehicles. All vehicles in this fleet are SMP. This fleet entered service in 1993. The original plan for retirement of this fleet was 2013, however, life extension is very likely. The fleet was reported to be “jury-rigged” in order to maintain the requirements [4]. Currently, a CPC (*i.e.* Krown T-40) is applied to the fleet vehicles annually.

The largest number of vehicles in the “B” Fleet are MLVWs, which include 2762 vehicles, plus 1348 special equipment vehicle (SEV) kits and 2186 trailers. This fleet entered service in 1982 and will be out of service by 2008. Advanced corrosion and structural damage were reported [4]. Presently, CPC is only applied to the vehicles in Atlantic Canada and the Depot in Montréal, and will continue until the fleet is replaced by the medium support vehicle system (MSVS) [5].

The HLVW fleet consists of 1210 vehicles; 783 cargo, 124 recovery, 46 tractor, 176 MFBT, 18 HMRT, 55 refuellers and 8 water tankers. This fleet is currently undergoing a major life extension program. Part of the HLVW life extension program addresses corrosion. A CPC is applied to this fleet annually, although the corrosion is not as significant as that on the LSVW and MLVW.

The “B” Fleet vehicles are life cycle managed by Directorate Support Vehicle Program Management (DSVPM) 3. Directorate Land Requirements (DLR) 6 is responsible for providing operational direction for the acquisition of all Army combat service support vehicles and equipment and for providing advice on their management. DLR 6 also has an overview of painting and corrosion protection of the vehicles, however DSVPM 3 is responsible for performing these activities

Limited information on the extent and cost of corrosion on the “B” Fleet vehicles is available. The Canadian Department of National Defence (DND) website [6] reported that in the fall of 2000, an inspection of the oldest fleet of logistics vehicles (MLVW), raised safety concerns about the wheel assembly. After 18 years in service, a large proportion of the wheel assemblies showed signs of advanced corrosion and structural damage, leading to considerable loss of integrity. The principle concern was that of safety. The wheels are a two-piece locking-ring type and failure of the wheel assembly could cause the locking ring to be expelled during tire maintenance.

A survey conducted by the Prairie Agricultural Machinery Institute [7] on the MLVM showed that corrosion of the cab is widespread in the MLVW fleet. It is estimated, through inspections at CFB Petawawa and CFB Gagetown, that 25% of the fleet has significant corrosion and that repairs would exceed the $4,500 repair expenditure limit (REL). The corrosion is most evident around the cab rocker panels, floorboards, and windshield sill. The increasing cost of repair as a result of corrosion and shortage of the repair parts for the critical and high usage components of the MLVW fleet in the near future led to the recommendation that the MLVW fleet be decommissioned by 2010.

In 2001, DSVPM 3 initiated a corrosion control and body maintenance program for combat service support vehicles. The program involved the application of Krown T-40, a CPC, to the vehicles. This product was chosen based on the evaluation studies conducted by Quality Engineering Test Establishment (QETE) [8] [9]

The current Standing Offer Agreement (SOA) with Krown, which ends May 2006, covers only the MLVWs in Atlantic Canada and the Depot in Montréal, making up approximately 33% of the MLVWs in the fleet. The future SOA will cover other fleets (*e.g.*, LUVW G-Wagon, the LUVW MILCOTS, SMP trailers, *etc.*) in addition to the existing ones.

It is estimatedthat the current SOA ($1.2 million) will increase to $1.9 million in the future SOA. With the increasing cost of the corrosion control and body maintenance program and reduced fleet size as a result of corrosion damage, there is an interest in a more proactive corrosion prevention program. The program should cover both procurement of new vehicles, and maintenance of existing fleets. In the sections that follow, a critical review of the recent developments in corrosion prevention programs in U.S. Army and research activities on army vehicle corrosion are presented. Most of the material presented were collected from the recent U.S. Army Corrosion Summit [3] and U.S. Tri-Service Corrosion Conference [2].

3 U.S. Army Corrosion Program

The 2002 U.S. Federal Highway Administration study, "Corrosion Costs and Preventive Strategies in the United States," conducted by CC Technologies, Inc. estimates that the annual cost of corrosion is $276 billion [1]. The U.S. Government Accountability Office has determined that $10 to $20 billion in direct costs can be attributed to military corrosion. The U.S. Department of Defense (DoD) Corrosion Office was recently formed to establish policy and standards on corrosion prevention and control within DoD. The goal of the Corrosion Office is to implement a long-term strategy to reduce corrosion and the effect of corrosion on the DoD's military equipment and infrastructure, thereby mitigating the safety, readiness, and financial effects of corrosion and reducing the logistics footprint.

The U.S. Army Corrosion Program is evolving from a selective, *ad-hoc*, tactical vehicle-focused, application program in the Pacific to a full spectrum of corrosion prevention and control technical and service functions, including aviation and soldier systems [10]. The U.S. Army's goal is threefold: (1) resolve corrosion issues on fielded equipment,

(2) upgrade designs to include safe, effective, low-cost corrosion prevention (3) control corrosion in manufacture and throughout the equipment's service life. The U.S. Army's test and evaluation programs, review and recommend safe and effective corrosion prevention and control technologies. Their goal is approving commercial off the shelf technologies that are suitable for military use while resolving technology gaps through research. The focus of the U.S. Army's corrosion program is on the Army Warfighter.

3.1 U.S. Marine Corps Corrosion Assessment Tool

The U.S. Marine Corps (USMC) has developed its own corrosion prevention and control program (CPAC). The goal is to establish an effective program to extend the useful life of all Marine Corps tactical ground and ground support equipment. For existing assets, the focus is on identifying and implementing new corrosion control products and maintenance procedures. For new procurements, the focus is on implementing corrosion control in the design stage.

As part of CPAC, USMC has developed a corrosion assessment tool for their ground combat and combat support vehicles. The checklist uses a Corrosion Category Code, which measures the level of maintenance required to return each asset to an operational ready state. A vehicle is assessed by working through the checklist of about forty questions that point to a final number between 1 and 5. A value of 1 means the asset is operationally ready and a value of 5 means that so much repair is needed that the asset should be scrapped. The checklist is performed on a PDA, which brings the time required to assess an asset down to about five minutes. The information from the PDA is downloaded to a PC to help fleet managers. The checklist covers five categories (Appendix A):

Category 1: Item requires no corrosion repair or preservatives, and has been assessed within the past 6 months. The goal at this level is to maintain the item as a category 1.

Category 2: Item requires surface preparation, spot paint, and preservation at the operator and/or organizational level. The goal of this effort is to return the item to category 1.

Category 3: Item requires maintenance performed beyond the operator level. Spot painting has arrested the corrosion, but the item is now in a condition that requires complete repainting and overcoat. The item must be inducted to the "Corrosion Control and Coating" (C3) program for repair. The goal of this effort is to induct the item into the C3 program so that it will return to the unit in a category 1 condition.

Category 4: Item requires repair to sheet metal, major frame components, paint, blasting and undercoating (*e.g.*, replacement or repair of components such as doors, fenders, and chassis frame rails, or battery boxes due to corrosion). The goal of this effort is to immediately induct the item into the C3 program so that it will return to the unit in a category 1 condition.

Category 5: The item is degraded to a degree that requires depot level repair and replacement based on the deterioration caused by corrosion.

An example of the data obtained from the Corrosion Assessment Checklist is shown in Table 1 [11]. In Table 1, a total of 306 HMMWVs (similar to the Canadian HLVWs) were evaluated using the checklist and assigned Corrosion Category Codes. The third column of Table 1 is an estimate of field-level expenses to maintain the same category for six months. The “rehab” cost is an estimate of the depot-level costs to bring the vehicles to category 1. By performing this evaluation it can be seen that it would cost $1.4 million to rehabilitate the 306 HMMWVs in Hawaii.

The U.S. Army is investigating the use of the USMC Corrosion Assessment Checklist to identify the extent of corrosion on their fleets. Adoption of a corrosion management tool such as the checklist would:

- Provide a quantitative measure from which to measure effectiveness of future efforts in corrosion control.
- Increase equipment readiness and availability
- Reduce negative operational effects (because problems are known and can be solved before the vehicle is used on a mission).
- Reduce maintenance burden on field units.
- Identify the annual corrosion costs requirement for individual vehicles and whole fleets.

3.2 Equipment Storage Technologies

There are two technologies for improving the storage conditions of equipment besides a climate-controlled indoor shelter—covering and dehumidification. Corrosion proceeds

Table 1: *An example of the corrosion category codes and their estimated costs for HMMWVs in Hawaii [11]. (CST is corrosion service team)*

Corrosion Category Code	Cost to Rehabilitate 306 HMMWV(s) (Current Process)			
	Qty	CST Cost	REHAB Cost	Total Cost
1 and 2	107	$27,392	0	$27,392
3	163	$41,728	$1,088,514	$1,130,242
4	36	$9,216	$240,426	$249,642
5	0	0	0	0
Totals	306	$78,336	$1,328,940	$1,407,276

when both high relative humidity and a corrodent (such as chloride) are present. Removing or reducing one or both of these reduces corrosion rates. One way to reduce corrosion is to protect the entire vehicle against the elements. In the Canadian Army, the “A” Fleet vehicles are stored inside garages whereas the “B” Fleet vehicles are stored outside; some with a plastic wrap.

3.2.1 Equipment Covers

Equipment covers are designed to reduce the corrosion of vehicles or large objects during storage outside. The covers have a drawstring around the edge and can be shrink-wrapped to form-fit around an object. The cover consists of three layers: (i) the outer layer is a UV-resistant polyethylene shrink/stretch film which holds its properties in extreme temperature, (ii) the middle layer is an adhesive and (iii) the polyester inner layer, is impregnated with a vapour phase corrosion inhibitor (VpCI). The VpCIs supposed to sublime from their source and adsorb onto metal surfaces as one or two monolayers that inhibit corrosion. Suppliers of equipment covers include Transhield [12] and Cortec Corp. [13]. An example of a howitzer cover from Transhield is shown in Figure 1 [12] [14].

Figure 1: *Image from Transhield commercial literature illustrating cover on the body of a howitzer. (Transhield, The Shrinkable Fabric (2006) `www.transhield-usa.com/military.html`)*

Equipment listed by Transhield as being currently protected with these covers includes:

- Guns and gun parts
- Engines & transmissions
- Construction machinery
- Communication equipment
- Motor vehicles and parts
- Aircraft engines and parts

Cortec Corp. also supply VpCI products and systems for storage and preservation of military vehicles. Recently, the U.S. Air Force (USAF) evaluated Cortec VpCI products and systems in deep storage and preservation (up to 12 months) of the military vehicles [15]. Many other VpCI products were applied prior to applying VpCI protective covers, including cleaning compounds, CPCs for various purposes, and lubricating oil. The UAF concluded that the VpCI products provide superior corrosion protection even in extreme atmospheric conditions. The entire VpCI storage approach is simple and efficient. After one day of training, the USAF team was well-versed in the technique. Table 2 presents a brief analysis of man-hours and VpCI product cost for various vehicle types. Evaluation showed that an average breakout time of 18 minutes, including the removal of the cover and actual vehicle start-up. Only a few minutes were needed for cover removal regardless of asset size. It was not necessary to remove other VpCI products.

Table 2: *Cost and labour/man-hour for application of VpCI to different types of assets [15]*

Vehicle	**Application (man-hours/unit)**	**VpCI Product Cost (US $/unit)**
Average of 120 vehicles	4.14h	$338
HMMVW	2.69h	$160
40K air cargo loader	7.5h	$795

3.2.2 Dehumidification

Creating an environment with 30–40% relative humidity can suppress atmospheric corrosion [16]. Logis-Tech Inc. [17] supplies the U.S. armed forces with dehumidification equipment. An example of equipment receiving dry air within a shelter is shown in Figure 2. Dry air can also be supplied to equipment outside of a shelter by using the vehicle hull as the envelope. In Canada, Munters [18] has supplied DND with portable dehumidification units. Martin claims that the following benefits are achieved with dehumidification [16]:

- Achieved life-cycle 10-year return on investment of 7.4 to 1, *i.e.*, for every dollar spent on dehumidification, eight fewer dollars were spent fixing rust and corrosion.
- Seventy percent of the life-cycle return on investment (ROI) was included in military technicians' manpower.
- Eliminated corrosion, dry rot, and leaks.
- Eliminated deterioration of fuel and fluids.
- Reduced maintenance man hours by 30 to 50%.
- Reduced preservation costs by 20 to 30%.
- Maintained 100% of weapons as combat-ready with 50% of personnel.

Figure 2: *Example from J.H. Martin of equipment receiving dry air through manifold system and vehicle interface adapters at Marine Corps Logistics Base, Albany, Georgia. (Martin, J.H. (2005). Atmospheric Corrosion Suppression Through Controlled Humidity Protection — An Operational Readiness and Force Multiplier. Materials Performance,* ***61****, 38.)*

4 Corrosion Preventive Compounds

Corrosion preventive compounds (CPC) are fluids that are used in a temporary capacity to provide an extra layer of protection for equipment where the original protective coating has degraded. They can be classified by the type of film they develop after curing, *i.e.*, hard, waxy or oily.

A brief review of the CPC studies conducted by the Australian Defence Science and Technology Organization (DSTO), QETE, and Royal Military College (RMC) of Canada is presented in this section.

4.1 Defence Science and Technology Organization

The effectiveness of CPCs has been studied extensively by DSTO [19]. Although most of this work was performed in the context of aircraft, many of the results are transferable to army vehicles.

One DSTO study examined the use of CPCs to prevent crevice corrosion on the chassis rails of Royal Australian Air Force fire trucks. This study investigated LPS-2 and Ardox 3961, both greatly reduced crevice corrosion on steel samples bolted into a sandwich exposed to wet/dry cycles of either tap water or fire fighting foam [20]. It was recommended that (i) after each exposure to fire fighting foam that the chassis be thoroughly rinsed, (ii) wherever corrosion is found, and there is sufficient access, the corrosion should be removed and the chassis repainted and (iii) in areas of limited access, a CPC should be applied on a regular basis [20].

A study on the effectiveness of nine CPCs for an aircraft application was presented at the 2003 Tri-Service Corrosion Conference [21]. Alloys AA2024-T3, AA7075-T6, and heat-treated 4130 steel were tested as both single metal and galvanically coupled lap joints. An accelerated corrosion test (General Motors GM9540/P [22]) was used because of its solution chemistry and the range of temperature, humidity, and wetness conditions. Nine different CPCs were evaluated, including examples of oily, soft film forming, and hard film forming CPC products. CPC effectiveness was evaluated on the basis of weight loss measurements. Laboratory performance has been shown to depend on the alloy protected and specimen geometry. DSTO concluded that two physically similar CPCs may have very different performance characteristics [21]. Oily thin film forming CPCs appear to be the best at suppressing corrosion in occluded geometries due to good wicking ability. One week of pre-corrosion and 4 weeks of exposure under GM9540/P conditions produced the most distinguishable differences in CPC performance for single metal lap joints. The driving force for corrosion in galvanic lap joints was high. It can be concluded that materials involved, the service environment, and the structures to be protected should be considered before any CPC is applied.

4.2 Quality Engineering Test Establishment

In 1999, DSVPM requested QETE to evaluate CPCs for application to Canadian Army vehicles [8] [9]. QETE first developed a methodology for evaluation of corrosion on parts treated with CPCs. A sandwich-type panel that was developed by the automobile industry was chosen to simulate crevice corrosion. The sandwich was comprised of two panels separated by a spacer and fastened together with low-grade steel bolts. The corrosion testing was conducted in accordance with ASTM 117. QETE also developed a methodology for the evaluation of other properties of the CPCs [9]. These properties include creep, penetration, water displacement, lubrication, wear resistance, compatibility with the paint used on the vehicles, flash point, and dielectric breakdown voltage. Table 3 lists the test method used to evaluate each property and the established limit.

Seven CPCs (*i.e.*, Rust Block, Dura Tech 2000, Dura Tech Plus, Rust Check, Krown T-40, #900 Rust Proofing Oil, and Fluid Film) were evaluated by QETE. It was found that only Krown T-40 met all the established property limits.

4.3 Royal Military College of Canada

The purpose of the RMC study was to develop tests that characterize the ability of a CPC to prevent outdoor corrosion and to quantify undesirable effects [23]. The device used to measure corrosivity was the CLIMAT (<u>CL</u>assification of <u>I</u>ndustrial and <u>M</u>arine

Table 3: *Test method and established limit for the properties of CPCs as determined by QETE [9]*

Property	**Limit**	**Test Method**
Flash Point	200°C min..	ASTM D92 (Cleveland open cup)
Lubricating Characteristics	1.25 Max.	ASTM D2266 (four-ball method)
Kinematic Viscosity at 100°C	6 cSt min.	ASTM D445
Non-conductivity	10 KV min.	ASTM D877
Water Diplacing	No abnormal stain shall appear	Federal Test Method Std. No. 79, Method 3007.2, water displacement
Corrosion inhibiting	Rust are 3% Max.	ASTM B117

ATmospheres); also known as the wire-on-bolt coupon. The CLIMAT is an outdoor exposure test that requires only three months. The corrosion of aluminum wire on the CLIMAT, is accelerated by a galvanic connection to a dissimilar metal threaded bolt. The RMC study used a slightly modified CLIMAT with three sets of aluminum wire around copper bolts as shown in Figure 3. The mass loss of aluminum is interpreted as a measure of corrosivity. The accelerated corrosion rate is 95% due to the galvanic connection and 5% due to the presence of crevices in the threads.

The effectiveness of nine CPCs was tested by applying them to CLIMATs and exposing them to the environments at four locations. The nine CPCs are listed in Table 4. The four locations were: (i) urban, RMC pedestrian bridge, (ii) rural, St. Anne, outskirts of Montréal, (iii) urban/industrial, St. Jean Baptiste, Montréal and (iv) rural, CFB Trenton.

Figure 4 shows the percent reduction in corrosion, relative to a control, for the nine CPCs at both CFB Trenton and St. Jean Baptiste, Montréal. Only these locations are shown

Table 4: *Name of each CPC tested and its manufacturer*

CPC	**Manufacturer**
WD-40	WD-40 Products (Canada) Ltd.
Corrosion Free, Formula 3000	Canadian Tire
ACF-50	Lear Chemical Research Corp.
LPS-2	LPS Laboratories
Krown T-40	Krown Body Maintenance
Rustcheck Dripless	Rust Check Corp.
Corrosion Block	Lear Chemical Research Corp.
Boeshield T-9	PMS Products Inc.
Rustcheck Red	Rust Check Corp.

Figure 3: *CLIMAT unit with three bolts of copper with aluminum wire.*

because they are extremes. The average mass loss for the control sample at CFB Trenton was 0.8%, while that of St. Jean Baptiste was 3.7%. These results indicate that the CFB Trenton climate was more benign than that of St. Jean Baptiste. At CFB Trenton, the CPCs were effective with all having above 85% inhibition. By contrast, the CPCs showed a range of inhibition from 28% to 83% at the St. Jean Baptiste site. In a benign environment, the CPCs tested, performed equally well. In more severe environments, the choice of CPC is important. of the CPCs tested, Corrosion Free, Formula 3000 showed the most corrosion inhibition.

The exposure testing also showed that some CPCs attracted more dirt and debris than others. An example of a control and a CPC treated CLIMAT is shown in Figure 5. The accumulation of debris may be particularly unwanted in some cases. The degree of debris that accumulated was non-destructively quantified using image analysis software (Corel Paint 10®). The blackening index was introduced to indicate the extent to which the dirt and debris attached to the CPCs. A darkening of unity (1) means no difference with the control and higher than unity indicates an increasing degree of darkening relative to the control. The average darkening index for the nine CPCs at four locations is shown in Figure 6. There are wide variations in the tendency of a CPC to collect debris when exposed outside.

The Canadian DND is interested in a complete corrosion program. When considering a program, the ability of a product to inhibit corrosion is only one part. Other considerations include environmental impact (*i.e.*, is the CPC a "green" product; does it contain solvent/high VOCs) and how much manpower will be needed for application of the CPC.

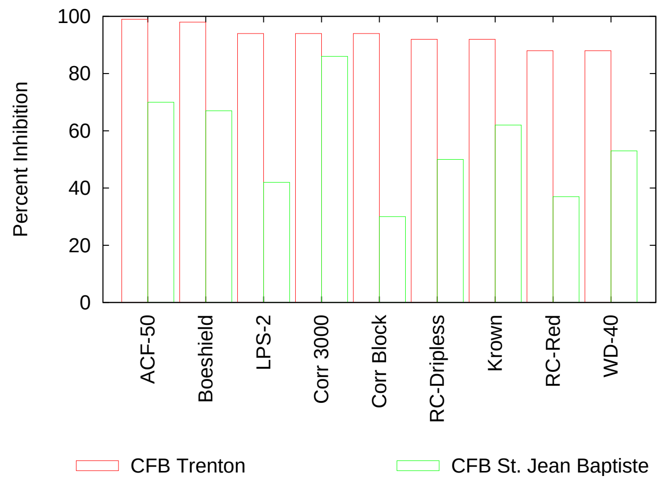

Figure 4: *Percent inhibition of corrosion of CPCs at (a) CFB Trenton (rural) and (b) St. Jean Baptiste (urban/industrial).*

Figure 5: *Control and CPC treated (Corrosion Block) CLIMAT after exposure at St. Jean Baptiste, Montréal.*

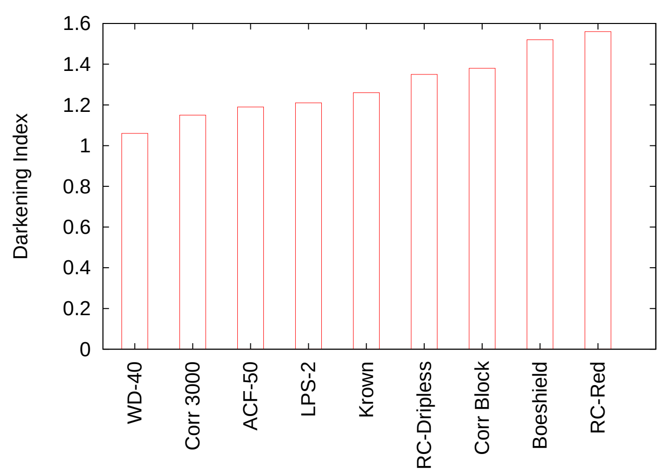

Figure 6: *Average darkening index for the nine CPCs at four locations.*

4.4 Collateral Damage to Materials From CPC Uses

There is a TTCP Operating Assignment on the collateral damage to materials from the application of CPCs with Dr. Terry Foster (Head/Dockyard Lab Pacific, DRDC Atlantic) as the representative for Technical Panel 6 (Polymers, Coatings and Adhesives). In an email from Dr. Foster [24], he reported that they have not done anything on non-metallics yet. The project will look at how easily CPCs are removed from painted surfaces, to see if there was any residual material left and what effect that has on re-coating and coating adhesion. At CFB Esquimalt, exposure testing can be performed at an outdoor atmospheric site or in the lab under alternating salt fog.

The USAF CPAC has identified the importance of the compatibility of CPCs with vehicle fluids and other CPCs [25]. In a recent conference proceedings, the USAF CPAC claim that some of the hardening types of CPCs become soft and fail to cure when exposed to hydraulic fluids [25]. There was general concern with the compatibility of CPCs with wiring insulation, seals, gaskets, *etc.*.

5 Coatings

Typical coating structures for an automobile and an army vehicle are shown in Figure 8. Both have a zinc layer above the metal substrate. This can be from either a zinc-rich primer or from a metallurgical process such as dipping, thermal spraying or electroplating. The zinc layer acts as both a barrier and a sacrificial anode where the barrier is broken. The metal coating is designed to preferentially corrode before the underlying steel. An automobile is electrocoated by dipping the assembly into a bath and electrodepositing an organic film. Electrocoating is used for priming and painting, instead of more traditional spraying, dipping or brushing methods. For an army vehicle, a primer and then a chemical agent resistant coating (CARC) are usually applied over the zinc layer. CARC is a polyurethane-based coating that is highly crosslinked to resist chemical attack.

An exception to the above approach for army vehicles was in the original design of the High-Mobility Multipurpose Wheeled Vehicle (HMMWV). The frame rails were made of 1010 carbon steel with no galvanizing protection and no provisions for draining water out of the interior cavities in the rails. Water, salt, and mud could accumulate in the cavities within the frame rails and cause corrosion of the painted steel. Newer HMMWV frame rails are now being galvanized (zinc-coated) and electrocoated.

5.1 Recent Developments in New Coating Materials

Attention has been paid to the development, testing and evaluation of the new coating materials that could potentially serve as alternatives to chromate, cadmium, and heavy

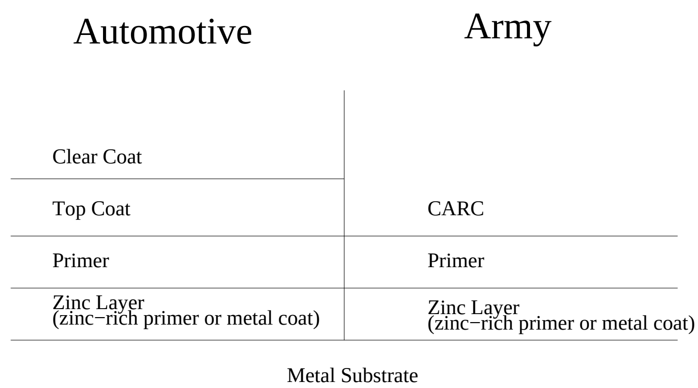

Figure 7: *Typical coating layers for automotive and army vehicles.*

metal coatings [2] [3]. Soluble chromates are still the most effective corrosion inhibitor for aluminum alloys. Applications include chromate in deoxidizers, conversion coatings, anodizing, chromate-inhibited primers, wash primers and repair processes. However, hexavalent chromate (Cr (VI)) is a known carcinogen that is to be eliminated in the near future. In the U.S., the exposure limit to Cr (VI) will be reduced from the current 52 $\mu g/m^3$ to 1 $\mu g/m^3$ in 2006. The following sections outlined some of the recent research activities in coating materials.

5.1.1 Self-healing Coatings for Aluminium and Steel

TDA Research Inc. has been working on corrosion inhibiting nanocomposite epoxy primers for aluminium alloys and steel [26] [27]. The nanoparticles are dispersed in standard epoxy resin. The pH change in the substrate/coating interface when corrosion occurs, causes the corrosion inhibitor to be released from the nanoparticle, stopping the corrosion. Nanoparticle based corrosion inhibitors have demonstrated very good performance for protection of steel and aluminium.

Another self-healing coating incorporates microcapsules (60-150 μm in diameter) into the paint primers used at the time of coating application. When the coating is scratched, the microcapsules break and spill corrosion inhibitors and film formers, which protect the underlying steel substrate from corrosion, and repair some of the coating damage.

5.1.2 Electroactive Polymer and Conductive Polymer Coatings

NAVAIR has successfully synthesized a new electroactive (EAP) polymer (2,5-bis (N-methyl-N-hexylamino) phenylene vinylene), which could serve as a viable alternative to chromate conversion coating pretreatment for aluminum alloys [28]. The films were sprayed onto an aluminum 2024-T3 substrate. Various electrochemical techniques were used to characterize the electroactive polymer films coated onto aluminum 2024-T3 coupons. The electroactive polymer pretreatment has passed the required 336-h neutral salt fog exposure test for corrosion resistance.

Smart coatings that respond to corrosion processes at the metal surface have been investigated [28]. The smart coating systems are engineered to respond to the electrochemical processes responsible for corrosion and provide a self-repairing system. Smart coatings utilize electroactive polymers such as polyaniline to capitalize on their ability to (1) conduct electricity, and (2) bind and expel molecules or ions in response to an electrochemical potential. For a smart coating system, the electrochemical corrosion reactions at the metal surface act to change the redox state of the coating. The coating can be engineered to release organic oxygen reduction reaction inhibitors when its redox state changes. The rapid release of inhibitors in a localized area acts to shut down the corrosion process.

Inherently conductive polymers (ICP) combined with military specification primers and/or topcoats are another technology being investigated to provide protection in highly corrosive environments [29]. The ICP coating provides cathodic-sacrificial protection by preferentially corroding before the metal substrate. The ICP corrosion products are insoluble and precipitate onto the substrate, providing an additional degree of protection to the damaged area. This self-healing nature of the coating extends its service life and allows more time between scheduled maintenance. The US Army is investigating ICPs under the US Army Technology Demonstration for Provention of Material Degradation Program [29].

DRDC Atlantic is proposing a TTCP Operating Assignment for Technical Panel 6 (Polymers, Coatings and Adhesives) on conducting polymers for CPCs.

5.1.3 Active Coatings

The Army Corrosion Office at Picatinny, NJ, the New Jersey Institute of Technology, Clemson University and the University of New Hampshire are collaborating to develop active coatings [30]. The goals of these activities are to produce multifunctional coatings. Beside corrosion resistance, it is envisioned that these coatings will provide real-time active sensing (of chemicals), self-repairing, coloring attributes and the ability to alert logistics staff when extensive repair is necessary. Some of these properties will be tailored into the coating material, while a system of embedded sensors with wireless capability is seen as providing other functionalities.

5.1.4 Surface Mineralization

Surface mineralization is an environmentally benign process that forms a thin metal silicate surface fully involving the substrate metal [31]. This surface treatment can be used as an alternative to cadmium plating and hexavalent chromate for corrosion protection. This mineralizing technology is available as an electrolytic process as well as gel and lubricant forms for use in protection of deck machinery systems. This technology is currently being used by the U.S. Navy in the corrosion protection upgrade of weather deck steel watertight door docking mechanisms, as a corrosion inhibitor for shipboard anchor chain detachable links, and for corrosion protection of aircraft carrier elevator wire ropes [31]. This technology is also being used in U.S. Army for cadmium replacement for legacy vehicles [31].

5.1.5 Rare Earth Based Coating

The toxic nature of hexavalent chromium has led to the study of rare earth metals for replacement technologies [32]. Research into rare earth metals started in the 1980s and since then they have been shown to be effective as inhibitors for ferrous metals [33], aluminum alloys [34], conversion coatings [35], and deoxidizers [36].

5.1.6 Other Coating Materials

A zinc-rich, water-based primer, which is a potassium-silicate-based material with no VOC and no flash point can be used to extend the service life of vehicles [37] [38]. In a study of several types of zinc-rich primers and zinc platings in the ASTM B117 salt fog test and cyclical SAE J2334 corrosion test (designed to simulate de-icing road salt), it was found that this primer performed well.

Another paint system of interest is Por-15 Rust Preventative Paint (www.por15.com) [39]. This coating involves moisture-cured polyurethane that is designed to go directly onto rusted or seasoned metal surfaces and concrete. It cures to a hard, non-porous finish.

Another type of coating that provides corrosion protection at a higher price than paint is appliqués. These are films of fluoropolymer with pressure sensitive “peel and stick” technology. The tape forms an almost perfect barrier to moisture [40]. The benefits to appliqués are that they (1) impart excellent corrosion protection/chemical resistance, (2) are easy to apply to existing structures, (3) no VOCs/solvents are used during application, and (4) have multifunctional capabilities.

5.2 Surface Preparation Techniques

Nanoceramic-based conversion coating is a more environmentally benign alternate surface preparation technique to phosphating of steel surfaces [41]. This conversion allows the production of nanometer thin coatings, while traditional phosphate layers exhibit micron thicknesses. Nanoceramic coatings are based on the combination of a nano-structured ceramic-type metallic oxide, with metals like titanium and zirconium. The nanoceramic conversion is industrially applied in a multi-stage process, which includes an alkaline cleaning step, rinse, acid conversion, and deionized water rinse. The application can be performed at ambient temperatures. Neutral salt spray (NSS) tests according to ASTM B-117 or ISO 9227, and cyclic corrosion testing according to the GM 9540 P standard have been used to assess the coating's corrosion resistance when applied to aluminum, cold-rolled steel and electrogalvanized steel. On all three substrates, the nanoceramic conversion shows very narrow creep from scribe and better performance than the standard phosphate coating.

Another surface pre-treatment uses silane chemistry [42]. On electrogalvanised steel, hot dip galvanized steel, and aluminium alloys (Al 6061, Al 6111), the silanes bis-(trimethoxysilyl-propyl)amine (bis-amino silane) and bis-(triethoxysilylpropyl)tetrasulphide (bis-sulphur silane) were found to provide excellent corrosion protection in conjunction with the electro-coat ED-5000 (PPG Industries Inc.). On cold rolled steel, a mixture of the above two silanes provided corrosion protection comparable to the currently used zinc phosphate system. The corrosion performance of automotive steels pretreated with silanes has been compared with that of zinc phosphated steels using a variety of tests including the GM scab test, electrochemical impedance spectroscopy, and N-methyl pyrrolidone adhesion tests.

5.3 Techniques for Testing Coating Materials

There are basically three approaches for testing coating materials—outdoor exposure, accelerated cabinet tests and electrochemical tests. The standard is outdoor tests that normally take 1–10 years. However, when results are required on a shorter timescale, more rapid testing can be performed.. Accelerated cabinet tests include:

- ASTM B 117 Standard Practice for Operating Salt Spray (Fog) Apparatus
- ASTM B 368 CASS Test
- ASTM B 380 Corrodkote Test
- ASTM D 1735 Water Fog
- ASTM D2247 100% Relative Humidity
- ASTM G85 Modified Salt Fog (Annex 1, Annex 2, Annex 3 and Annex 5)
- GM 9540 P Cycle B
- SAE J 2334
- SCAB tests
- Ultraviolet exposure-ASTM G53

The ASTM B117 test calls for a continuous fog of 5% salt solution at 35°C. This may be useful when making comparisons between the performance of different coatings, but there is a lack of information correlating these tests to real time corrosion data [43]. The ASTM G85 test is a modification of ASTM B117. The annexes of ASTM G85 call for different conditions, including: continuous acetic acid-salt spray, cyclic acidified salt spray, seawater acidified spray, SO_2 salt spray, and dilute electrolyte cyclic fog/dry stage. During the 1980s a task force was established by the American Iron and Steel Institute (AISI) with the goal to develop a laboratory accelerated test for cosmetic corrosion resistance that would provide a reliable ranking of automotive sheet steel products. This work led to the development of the cyclic SAE J2334 test. This test typically gives the best correlation with 5-year on-vehicle corrosion tests. SAE J2334 has an initial humid stage of 6 h at 50°C and 100% R.H., followed by a 15 min. salt application stage with 0.5% NaCl, 0.1% $CaCl_2$ and 0.075% $NaHCO_3$ at 25°C. The final stage is 17.75 hours at 60°C and 50% R.H. An AISI-sponsored study showed that 80 cycles corresponded to about 5 years of outdoor exposure in a severe location like Montréal [44].

The integrity of coatings can also be tested using electrochemical means. Coated samples can be placed in a solution of choice and assessed by electrochemical impedance spectroscopy (EIS). Through analogies with analogue electrical circuits, the coating resistance, capacitance and metal corrosion rate can be interpreted.

6 Sensors

Sensors can be either passive or active and measure either corrosivity or *in situ* corrosion rates. Corrosivity is the average corrosion rate of a metal sample over a known exposure time, while the data obtained from observation of corrosion on a metal *in situ* is referred to as a corrosion rate. A passive sensor requires no power or electronics, examples include the CLIMAT coupon or simply sample of the metal of interest. Passive sensors reveal the corrosivity of the sample metal. An active sensor is electronically powered and can provide a semi-continuous measure of either *in situ* corrosion rates or corrosivity.

6.1 Corrosivity Sensors/Coupons

Coupons are the traditional method for measuring corrosivity and have been described in a number of places in the literature. Usually the coupon is exposed to a corrosive environment to simulate an actual component or structure. After exposure, the coupon is weighed and examined microscopically. Coupons provide an inexpensive, yet effective way to measure corrosivity in a system.

6.2 Corrosion/Coating Sensors

There are two active sensors designed to measure *in situ* corrosion rate and/or coating integrity under commercial development. The first is a technology designed to monitor the health of coatings on vehicles from DACCO SCI INC. [45]. It is an extrapolation of a well-established laboratory technique called electrochemical impedance spectroscopy (EIS). The sensors are designed to be attached to critical areas of a vehicle. The sensors measure and record coating impedance, which is related to coating integrity. A counter electrode is placed on top of the coating and the working electrode is the metal substrate. Coatings in good condition exhibit high impedance at low frequencies whereas the impedance decreases as a coating degrades. Information on the corrosion rate of the underlying metal is also revealed. The goal is to market these sensors for $100 (U.S.) per sensor; they are not yet commercially available. The second technology embeds the counter electrode at different levels of the coating [46]. This approach has advantages over traditional EIS techniques because it can detect phenomena that might be occurring beneath the surface of the coating. This work is preliminary, and no commercial product is currently available.

6.3 Condition-based Monitoring and Maintenance

Any *in situ* measurement of metal corrosion rate and/or coating integrity could be used to provide condition-based monitoring. However, as mentioned previously, although EIS-based sensors are promising they are not "off-the-shelf" technologies yet (see §6.2). A technology that is promising and currently available is flash thermography. It is a non-destructive inspection technique where a surface is "flashed" with a radiant heat source and the infrared emission from the surface is monitored with a video camera. Patterns of surface temperature can reveal corrosion under the paint and backside corrosion [47].

7 Options/Recommendations

In order to increase the equipment readiness, availability and service life, and to reduce the ownership cost, it is necessary to implement a comprehensive corrosion control program to minimize the corrosion damage to the Canadian Army vehicles. The program should include the following aspects:

1. *Start at design stage.* For the new vehicles, the corrosion control program should ensure that cost-effective new coating materials and coating application technologies be adopted on the new vehicles.

2. *Corrosion survey.* For the existing vehicles, a survey should be conducted to assist in identifying the extent of corrosion and mitigation cost. It is recommended to

start with the USMC corrosion management tool (Appendix A) and modify it to suit Canadian needs.

3. *Condition-based maintenance.* The current corrosion control and body maintenance program calls for annual application of a CPC to the vehicles. A condition-based maintenance program (including CPC application) should be implemented to maintain the vehicles. The optimal frequency of a CPC application depends on the environment to which the vehicle is exposed. A vehicle in a benign environment needs CPC application far less frequently than one exposed to a severe environment. The volume and location of CPC application also influences the level of vehicle protection. Answers to these questions require a combination of laboratory and field measurements, possibly through the use of *in situ* sensors. The program should also ensure that any required repair to a vehicle as a result of corrosion be done at its earliest possible stage.

4. *Use advanced storage technologies.* The effectiveness of storage technologies currently used can be evaluated by placing sensors (*e.g.*,CLIMATs, steel coupons and temperature/relative humidity loggers) within the equipment being stored. Consider using the new storage technologies (*e.g.*, VpCI protective covers, dehumidification) if the current technologies are found to be deficient. DSVPM 3-16 is already investigating VpCI technologies, and their findings should be incorporated into the corrosion control program.

5. *Adopt new coating repair techniques.* The program should ensure the use of new coating materials and of appropriate coating repair technique.

Appendix A: US Marine Corps Corrosion Assessment Checklist

UNITED STATES MARINE CORPS
CORROSION ASSESSMENT CHECKLIST

ASSESSED BY: ______________________ (RANK / LAST NAME)	DATE OF ASSESMENT: ______________ (dd/mmm/yyyy)
AAC: _____________________________	MANAFACTURER DATE: ______________ (mmm/yyyy)
NSN: ______ - ____ - _____ - ______	TAMCN: _________________________ (OPTIONAL ENTRY)
USMC SERIAL#: ___________________	TYPE PAINT: _____________________ (CARC / WB-CARC / WR-CARC)
CARC PAINT DATE: ________________ (mmm/yyyy)	CATEGORY CODE: _________________ (MAX Category indicated below)

(Reference: TM 4795-12/1)

CATEGORY 5
(Corrosion Repair and Efforts above the Intermediate Level)

YES NO

☐ ☐ **FRAME** is **unsound** or completely gone ("unsound" means that the mechanical strength is lost). Select which best describes the condition of the frame:

- ☐ Deterioration due to severe corrosion
- ☐ Severe Mechanical/Physical Damage (e.g. bent frame)

☐ ☐ **OVERALL ITEM CONDITION** has severe mechanical damage or deterioration to a degree that presents a safety hazard and requires replacement based on:

- ☐ Deterioration due to severe corrosion
- ☐ Severe Mechanical/Physical Damage

CATEGORY 4
(Corrosion Repair and Efforts above the Organizational Level)

YES NO

☐ ☐ **FRAME** remains structurally **sound** but requires **REPAIR to METAL** prior to surface preparation or recoating above the organizational level due to:

- ☐ Deterioration due to severe corrosion
- ☐ Severe Mechanical or Physical Damage

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☐ ☐ **MAJOR FRAME COMPONENTS** (chassis frame rails on HMMWV(s) or support frames on cargo trailers) remain **structurally sound** but require **REPAIR** prior to surface preparation or recoating due to:

- ☐ Deterioration due to corrosion
- ☐ Severe Mechanical or Physical Damage

☐ ☐ **CAB COMPARTMENT** has deteriorated and requires metal **REPAIR** or **REPLACEMENT** prior to surface preparation or recoating due to:

- ☐ Deterioration due to severe corrosion
- ☐ Severe Mechanical or Physical Damage

☐ ☐ **FLOORING** is unsound ("unsound" means that the mechanical strength is lost) and **METAL REPAIR** is required prior to recoating due to:

- ☐ Deterioration due to severe corrosion
- ☐ Severe Mechanical or Physical Damage

☐ ☐ **BODY PANEL(s) or PART(s) are** unsound or completely gone ("unsound" means that the mechanical strength is lost) and require metal **REPAIR** or **REPLACMENT** prior to recoating due to:

- ☐ Deterioration due to severe corrosion
- ☐ Severe Mechanical or Physical Damage

☐ ☐ **CREVICE(s), JOINT(s),** or **SEAM(s)** are unsound or completely gone ("unsound" means that the mechanical strength is lost), and metal **REPAIR** is required prior to recoating due to:

- ☐ Deterioration due to severe corrosion
- ☐ Severe Mechanical or Physical Damage

☐ ☐ **BATTERY BOX** area is unsound or completely gone ("unsound" means that the mechanical strength is lost), and **METAL REPAIR** is required prior to recoating due to:

- ☐ Deterioration due to severe corrosion
- ☐ Severe Mechanical or Physical Damage

☐ ☐ **OTHER EXTENSIVE PHYSICAL DAMAGE** that requires body **repair** and coating above the Organizational Level.

CATEGORY 3
(Corrosion Efforts above the Organizational Level)

YES NO

☐ ☐ **FRAME** is corroded but remains sound. Metal requires **only surface preparation** and coating above the Organizational Level.

☐ ☐ **UNDERCARRIAGE OR SUSPENSION** parts are corroded but remain sound. Metal requires **only surface preparation** and coating above the Organizational Level.

☐ ☐ **CAB COMPARTMENT** requires **only surface preparation** and coating above the organizational level due to:

- ☐ Corrosion
- ☐ Minor physical damage
- ☐ Extensive coating damage

☐ ☐ **FLOORING** requires **only surface preparation** and coating above the Organizational Level due to:

- ☐ Corrosion
- ☐ Minor physical damage
- ☐ Extensive coating damage

☐ ☐ **BODY PANEL(s)** or **PART(s)** require **only surface preparation** and coating above the Organizational Level due to:

- ☐ Corrosion
- ☐ Minor physical damage
- ☐ Extensive coating damage

☐ ☐ **CREVICE(s), JOINT(s),** or **SEAM(s)** require **only surface preparation** and coating above the Organizational Level due to:

- ☐ Corrosion
- ☐ Minor physical damage
- ☐ Extensive coating damage

☐ ☐ **BATTERY BOX** requires **only surface preparation** and coating above the Organizational Level due to:

- ☐ Corrosion
- ☐ Minor physical damage
- ☐ Extensive coating damage

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☐ ☐ The equipment requires **REPAINTING** of the camouflage pattern above the Organizational Level due to:

- ☐ Excessive spot painting
- ☐ Currently no camouflage pattern on equipment

CATEGORY 2
(Corrosion Efforts at the Organizational Level)

YES NO

☐ ☐ **UNDERCARRIAGE OR SUSPENSION** parts are corroded or have coating damage that require repair at the organizational level only.

☐ ☐ **Organizational Level corrosion control efforts** are required for:

- ☐ Cleaning
- ☐ Surface Preparation
- ☐ Spot Painting/Touch-up

☐ ☐ **RADIATOR AND COMPONENTS** require organizational level corrosion efforts due to:

- ☐ Surface corrosion
- ☐ Minor coating Damage

☐ ☐ **HYDRAULIC CYLINDER(S)** require preventive maintenance, or replacement at the Organizational Level due to:

- ☐ Corrosion
- ☐ Pitting

☐ ☐ **HYDRAULIC LINE CONNECTORS** are corroded and require Cleaning or Replacement at the Organizational Level.

☐ ☐ **ELECTRICAL CONNECTORS** require preventive maintenance or replacement.

☐ ☐ **FLOORING** requires surface preparation, and spot painting at the Organizational Level.

☐ ☐ **CAB, BODY PANEL(s)** or **BODY PART(s)** require surface preparation, spot painting, or replacement at the Organizational Level.

☐ ☐ **CREVICE(s), JOINT(s),** or **SEAM(s)** require surface preparation, and spot painting at the Organizational level.

☐ ☐ **BATTERY BOX** requires surface preparation, and spot painting at the Organizational level.

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☐ ☐ **BATTERY and TERMINALS** require Organizational Maintenance to:

- ☐ Perform Preventive Maintenance
- ☐ Apply Anti-Corrosion Materials and Preservatives

☐ ☐ **HEADLIGHT ASSEMBLY** requires replacement.

☐ ☐ **HOOD** requires replacement due to severe physical damage.

☐ ☐ **EXHAUST SYSTEM** requires replacement at the Organizational level.

☐ ☐ **REFLECTIVE LENSES** require replacement at the Organizational level.

☐ ☐ **FASTENER(s),(nuts, bolts, washers, wingnuts, etc.)** are corroded and require Cleaning or Replacement at Organizational Level due to:

(NOTE: Red Rust does not classify the item as category II)

- ☐ Paint Blistering, Chipping or Pitting
- ☐ Surface Corrosion Beyond Red Rust
- ☐ Require Preservation

☐ ☐ **PUSH/PULL CABLE(s)** require repair at the Organizational Level because they are:

- ☐ Corroded
- ☐ Seized
- ☐ Require Preservation

☐ ☐ **MIRROR(s), AND HARDWARE** require repair at the Organizational Level because they are:

- ☐ Corroded
- ☐ Seized
- ☐ Require Replacement

☐ ☐ **CORROSION PRESERVATIVES** are required on the asset.

CATEGORY 1 (Corrosion Efforts at the Organizational Level)

YES NO

☐ ☐ **ITEM is in a category 1 condition which** requires no corrosion repair and corrosion preservatives have been applied.

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