The Army's Pacific Rim Environmental Degradation of Materials Research Program

Improving Combat Readiness

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INTRODUCTION

The Pacific Theater of Operations (PTO), Figure 1, is the staging area for many of the US military's units. This region is also home to a vast array of assets, which include infrastructure, facilities, equipment, and vehicles from all of the services and the Coast Guard. In the state of Hawaii, for example, there are more than 100 military installations covering 200,000 acres, which is 5% of the land area. The US Army has the largest holding of the services with approximately 150,000 acres.[1] Much of the Army's materiel is moved within the PTO from location to location and as a result is exposed to the extreme environments that are present in the region. Material degradation is often accelerated in these harsh environments.

Figure 1. Pacific Theater of Operations.

To reduce the cost of material degradation and to improve combat readiness, it is important to understand the performance of materials in such environments. When formalized, this knowledge will lead to the development of best practices and methods for preserving and maintaining military assets that operate in these environments. Furthermore, material-environment compatibility can lead to component and system designs that are more resistant to degradation and thus result in a longer operating life for the system.

Pacific Rim Environmental Degradation Materials Research Program

With the vast array of environments that are scattered across the PTO and the substantial number of existing materials and possible materials combinations, it is an exceedingly difficult proposition to test each material-environment compatibility. However, through the Pacific Rim Environmental Degradation of Materials Research Program (PREDMRP) the US Army is taking advantage of the unique natural wonders of the Hawaiian Islands to accomplish much of this difficult task.

Hawaii is a premier natural laboratory because it has one of the most spatially diverse climates on Earth, representing that of a

Figure 2. Examples of Diverse Climates on Hawaii: Alpine (Top Left), Arid/Desert (Top Middle), Industrial (Top Right), Marine (Bottom Left), Rainforest (Bottom Middle), Volcanic (Bottom Right).

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miniature continent. Essentially there are several very different types of micro-climates and environments located within a relatively small region. The following micro-climates and environments can be found on the islands (see also Figure 2):

- Marine
- Temperate
- Rain Forest
- Desert
- Alpine
- Volcanic (producing acid rain)
- Industrial
- Agricultural

In order to capture the full effects of exposing Army materiel to a diverse set of climates, such as that found in the PTO, without expending a vast amount of monetary resources, the Army Corrosion Office (ACO) partnered with the University of Hawaii to set up testing facilities in the various microclimates readily found on the Hawaiian Islands.

History of the Program

The ACO, which is located at the Army Research Development and Engineering Center (ARDEC), initiated the materials testing research in 2003 as the Pacific Rim Corrosion Research Program (PRCRP). However, prior to this effort the Army began some precursory work on outdoor and laboratory accelerated testing of materials in 2001.

The PRCRP involved corrosion and climatology research in Hawaii and regions of the Pacific Theater of Operation. Corrosion mapping studies of Hawaii's microclimates, and corrosion studies of advanced composites, ceramics, ceramer (hybrid ceramic-polymer) coatings, and advanced electronics were conducted. Correlations between corrosion in controlled environments in the laboratory and corrosion in natural outdoor environments were also investigated.

To build on established testing facilities and expertise the ACO and the University of Hawaii began the follow-on program, the PREDMRP, in late 2006. The ongoing program is intended to mitigate long-term corrosion problems through applied research and the formulation of better test methods, coatings and material substitutes. The PREDMRP uses both laboratory and atmospheric testing to accurately predict material degradation and achieve the program objectives.

Overview of Tasks

The PREDMRP aims to reduce corrosion costs by developing a better understanding of the relationship between corrosion performance in the natural environment and accelerated corrosion tests. This will result in improved screening protocols and predictive capabilities such that materials requiring low maintenance can be identified and effective corrosion protection strategies can be developed. The PREDMRP also focuses on developing ways to assess corrosion and coating degradation, as well as developing novel ceramer coatings that have high resistance to solar degradation.

To accomplish these goals, the program focuses on four primary areas of research and testing:

- Atmospheric corrosion – effects of solar radiation, specimen orientation and sheltering
- Corrosion modeling
- Development of corrosion prototype sensors
- Corrosion protection strategies

This comprehensive approach will provide the Army with 1) a better understanding of the correlation between accelerated corrosion testing and performance in the natural environment for alloys and advanced materials, 2) predictive capabilities for corrosion behavior in atmospheric and immersed conditions, 3) the ability to assess corrosivity in real time with the utilization of sensors, and 4) strategies to combat corrosion using novel ceramer coatings and corrosion preventive compounds.

Table 1. Testing and Analysis Equipment Used to Study Materials Degradation.

Equipment	Purpose
Cyclic corrosion test chamber with fully programmable temperature, humidity and spray cycle capability	Performs accelerated corrosion testing including industry-standard accelerated corrosion tests, such as ASTM B117, GM 9540P and SAE J2334
Accelerated weathering chambers	Simulates sunlight, rain cycles, temperature and humidity
Dispersive Raman spectrometer	Analyzes coatings, polymer matrix composites, ceramics and corrosion products
Optical microscopes, including a scanning probe microscope	A variety of optical microscopes and image analysis software are used to characterize corrosion and surface morphology
Electrochemical quartz crystal nanobalance	Studies the growth of oxide films on electrodes
Fourier transform infrared (FT-IR) spectrometer with an Attenuated Total Reflectance (ATR) attachment and a Thermo-Gravimetric Analysis (TGA) unit	Analyzes coatings, polymer matrix composites and ceramics
Scanning electron microscope with energy dispersive X-ray	Analyzes microstructure and corrosion morphology and elemental composition of materials and corrosion products
Secondary ion mass spectrometer	Obtains chemical profiles of coatings. The data obtained helps to develop an understanding of the synthesis of new coatings.
Scanning Kelvin probe	Obtains potential profiles over specimens under atmospheric conditions to study corrosion
Scanning vibrating electrode/scanning ion electrode	Studies corrosion currents and pH profiles over corroding sites on specimens immersed in electrolytes
Nanoindenter	Measures mechanical properties of thin ceramer coatings
3D Non-contact profilometer	Measures parameters such as maximum pit depth and volume removed due to corrosion
Video Image Enhanced Evaluation of Weathering (VIEEW)	Quantifies damaged areas of corrosion specimens by using a combination of direct and diffuse lighting schemes to maximize the visual contrast between the damaged and undamaged areas of a specimen

University of Hawaii Capabilities and Facilities

The Army Corrosion Office has established a collaborative research relationship with the University of Hawaii to leverage the advanced materials testing and analysis equipment, facilities, and expertise provided by the university. The program utilizes materials preparation equipment, including a convection oven, drills, a hydraulic press, grinding and polishing wheels, low speed saws, a sputtering machine and ultrasonic cleaners to prepare specimens for testing. Table 1 lists some of the testing and analysis equipment being used to study the degradation of materials in various environments.

MICROCLIMATES AND TEST SITES

The Pacific Rim program has taken the established practice of placing atmospheric test racks on an oceanfront beach and expanded it to include testing in several aggressive microclimates. Field testing of materials degradation is performed in various microclimates at several different test sites. These test yards are comprised of a pair of 4' x 6' racks with a full instrumentation suite, including sensors for temperature, humidity, time-of-wetness, solar and UV radiation, rainfall, wind speed and direction, chloride deposition, and corrosivity. The test racks contain an array of coated and uncoated material substrates as well as materials in different configurations (e.g., galvanic couples).

The test yards are strategically located at eight sites (rainforest, arid, marine (two locations), agricultural, industrial, volcanic – acid rain, and high altitude – high solar radiation) and are set up to serve as long-term test beds for future research projects and programs. The diversity of climate and environmental conditions to which the test racks are exposed allows trends in corrosion data to be identified.

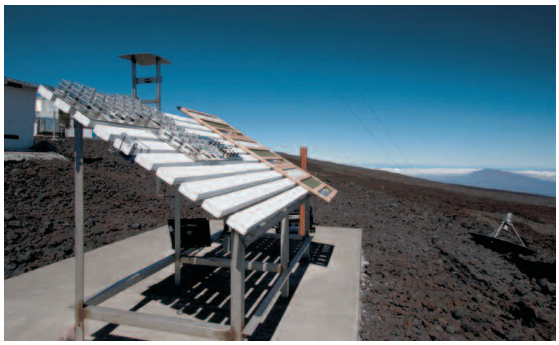

Figure 3. **Materials Degradation Test Yard at the Mauna Loa Observatory.**

Figure 4. **Coconut Island Materials Degradation Test Yard.**

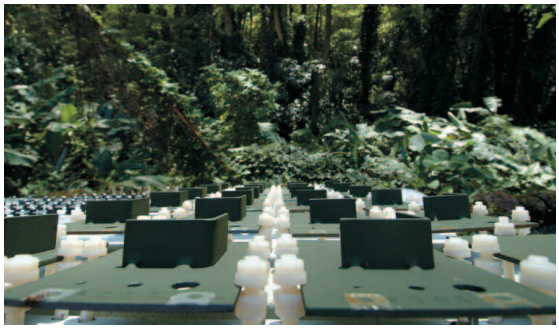

Figure 5. **Materials Degradation Test Rack in Rainforest Microclimate.**

Figure 6. **Materials Degradation Test Rack in Volcanic (Acid Rain) Microclimate.**

Alpine Microclimate (High Altitude)

The Earth System Research Laboratory's Mauna Loa Observatory on the Big Island in Hawaii hosts one of the program's test yards (Figure 3). The test racks are located at an elevation of approximately 11,140 feet above sea level, which is in an alpine microclimate, and they face northeasterly winds. This test site is characterized by high solar radiation, low temperatures, low humidity and rainfall, and low time-of-wetness. In addition, it is not entirely uncommon for this site to experience snowfall during the winter months. During a recent snow event the access road to the test site was closed due to heavy snowfall.

Marine Microclimate

Located across from the US Marine Corps Base in Kaneohe Bay, Hawaii, the Coconut Island test yard (Figure 4) is 25 feet from the shoreline and thus exposed to a severe marine environment. This site is characterized by high humidity and rainfall, low time-of-wetness, and high deposition rate of chloride ions.

Rainforest Microclimate

Another test yard is located at a University of Hawaii-owned site, Lyon Aboretum on the island of Oahu, which represents a tropical rainforest microclimate as it receives an average of 165 inches of rainfall each year. The test site (Figure 5) is located approximately 6 miles from downtown Honolulu and is characterized by high rainfall, high humidity, high time-of-wetness, and low chloride ion deposition rate. Based on recent findings this microclimate with high time-of-wetness can be as corrosive as many saltwater marine climates.

Volcanic Microclimate (Acid Rain)

Another test yard is located on Kilauea (Figure 6), which is an active volcano in Volcanoes National Park on the Big Island of Hawaii. Test racks are located in the path of the volcanic plume and near the ocean. This site is characterized by severe acid rain (primarily sulfuric and hydrochloric acids) with pH measurements as low as 3.

Arid, Industrial, and Agricultural Microclimates

The remaining test sites are located in agricultural, arid, and industrial microclimates. The arid environment is characterized by a stable, dry climate, which is found 14 miles from downtown Honolulu. The test yard exposed to industrial conditions is located in an industrial complex near refineries and power plants.

Portable Exposure Racks

In addition to the main test yards, the PREDMRP has developed portable exposure racks (PERs) to test materials performance and degradation in locations all over the island of Oahu as well as on Logistic Support Vessels (Figure 7). These portable test platforms have 13 substrates and 39 coupon specimens that are representative of many metal alloys that are used in Army items. The PERs are instrumented with a chloride candle, as well as temperature, relative humidity, time-of-wetness and corrosion sensors.

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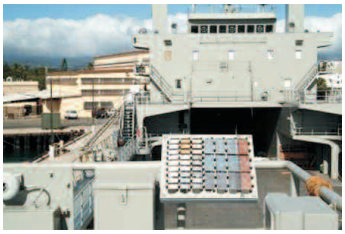

Figure 7. **Portable Exposure Rack on a Logistic Support Vessel.**

The University of Hawaii has established an agreement with the Hawaiian Electric Company and other local, state and federal agencies to apply more than 40 PERs at various locations throughout the Hawaiian Islands. This will enable the mapping of microclimates and corrosion effects throughout all regions of the islands.

RESEARCH PROGRAMS

Correlation Studies for Natural Environments

The PREDMRP is focused on four primary tasks, one of which is the study of atmospheric corrosion. This task includes several subtasks, which are briefly described below.

Specimen Orientation and Cross-Contamination

Under this task the effect of specimen orientation on cross contamination of corrosion products is being evaluated. The premise of this study is that exposure racks which house specimens of different compositions in certain configurations may be contaminated with byproducts of adjacent materials.

Mapping of Corrosivity

Also being performed under this task is an analysis of the deployment of portable exposure racks. The intent of this subtask is to characterize the atmospheric corrosivity of environments in which Army materiel are fielded in the PTO, which will help identify regions in Hawaii that have a similar corrosivity to other regions of the PTO. This will determine if materials can be effectively screened in Hawaii before deployment to other regions of the PTO. Another objective of this subtask is to build a database linking corrosion behavior of the thirteen metals on the PERs to weather and environmental data.

Corrosion Behavior of Metal-Matrix Composites

The corrosion mechanisms and corrosion protection strategies of continuous-fiber/aluminum metal-matrix composites (MMCs) and particulate-reinforced/aluminum MMCs are also being investigated. The corrosion behavior of these MMCs is being studied in natural and laboratory environments.

Materials Compatibility

One purpose of this subtask is to mimic corrosion of assembled components that are comprised of a variety of metallic and nonmetallic materials. The corrosion mechanisms and corrosion protection strategies of aluminum materials that are coupled to ceramics, ceramic-matrix composites (CMCs), and polymer-matrix composites (PMCs) are being studied under this task. The influence of environmental parameters is being investigated, and the behavior of the material couples in natural environments is being correlated to their performance in laboratory tests.

Testing Unexploded Ordnance Materials

Corrosion testing of 1040 steels, which are commonly used in munitions, is being conducted in various soil types. This study will provide the Army with information that can aid in the cleanup of buried munitions and unexploded ordnance (UXO).

Corrosion Modeling

The objective of this task is to develop corrosion models that accurately predict the occurrence and rate of corrosion in various environments. The models are being constructed based on experimental observations and relevant theoretical corrosion mechanisms. In this task, corrosion rates predicted by atmospheric models will be compared to actual corrosion rates observed on the PERs.

Corrosion models using computational fluid dynamics (CFD) are also being developed under this task to simulate and verify corrosion mechanisms of aluminum MMCs in immersed conditions. These corrosion models will be able to address two- and three-dimensional problems so that localized corrosion can be considered. The models will account for corrosion currents, pH, and the formation of corrosion products, and they can be used for other applications by modifying boundary conditions.

Corrosion Sensors

The objective of the third task in the PREDMRP is to develop and test prototype sensors in various environments to determine sensor characteristics. Sensors that have different geometric configurations are being investigated. In addition, researchers are studying the response of sensors to electrolytes with various chloride concentrations. The longevity of the prototype sensors is also being evaluated.

Time-of-wetness (TOW) is a critical parameter in corrosion studies and artificial leaf electrical resistance sensors are used to collect TOW data. The effect of a coating on the drying characteristics of the TOW sensors is being studied. Since the chloride content of rainwater may have a significant effect on the output of the sensor, it may also serve as a chloride indicator. Thus the TOW sensors are being studied to determine how the effect of chloride concentration affects the drying characteristics of the sensors.

Corrosion Protection Strategies

In the final task in the PREDMRP, novel ceramer coatings are being synthesized and evaluated as corrosion barriers. These silane-based ceramer coatings are being prepared via sol-gel process, and their chemical, physical, mechanical, and degradation properties and characteristics are being studied. The primary objective of this research is to develop a low-temperature curing, environmentally friendly coating that has reactive functionalities such that it can bind with a topcoat material. The ceramer coatings can also be used without additional topcoats. The research in this task will also include the testing and evaluation of commercial-off-the-shelf corrosion protection compounds in the climatic conditions described in this article.

CONCLUSIONS

With support from the University of Hawaii, the Army has established a state-of-the-art corrosion laboratory that is co-located with unique natural microclimate atmospheric testing resources. With this capability, the Army can support corrosion research, material analysis, testing and screening of corrosion preventive compounds, material degradation, and advanced ceramic-polymer coating development research. This enables the Army to access and interface with other DoD components in Hawaii and other regions of the PTO. The testing capabilities and resources are also positioned to provide support to other DoD organizations as well as industry and academia.

The climatic conditions being studied are not confined only to the PTO but are typically found worldwide in many operational

theaters. Because of the new reality of military action in the 21st century, armaments, systems and materiel may be pre-postitioned and deployed anywhere in the world and might encompass one or more of these climatic conditions.

The PREDMRP and its predecessor program, the PRCRP, have already achieved many objectives, including the development and deployment of a network of atmospheric corrosion test yards. The array of natural test sites will enable materials to be characterized in a broad spectrum of environmental and climatic conditions that are of interest to the Army. The determination and control of the corrosion behavior of advanced materials and electronics will be essential to the development of future combat systems with greater reliability and durability. The study of new corrosion-resistant coatings will help to reduce corrosion failures and costs. The study of buried munitions will help the Army to understand and reduce potential corrosion problems. Testing of commercial corrosion preventive compounds will aid the Army in screening products for use in various applications.

When the PREDMRP is complete, the research findings and developments will be integrated into useable design criteria for the material developer, system designer, and the end user. There are many potential benefits of the PREDMRP, including decreasing life-cycle costs of weapon systems, reducing the associated maintenance and liability costs, and increasing Army readiness by reducing equipment downtime. Based on the successes of the program, the Army plans to support future projects including performance of long-term atmospheric testing of actual Army components.

Historically corrosion in the DoD has been regarded as a maintenance problem to be dealt with after a product is manufactured and handed off to the warfighter. However, through the research performed under this program corrosion can be addressed in the design stage instead of relying strictly on costly and repetitive maintenance procedures that occur throughtout a product's lifecycle.

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