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Corrosion Protection of Launch Infrastructure and Flight Hardware at the Kennedy Space Center

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Abstract

The Kennedy Space Center (KSC) is a major source of worldwide corrosion expertise. Corrosion studies began at KSC in 1966 during the Gemini/Apollo Programs with the evaluation of long-term protective coatings for the atmospheric protection of carbon steel. NASA's KSC Beach Corrosion Test Site was established at that time. The site has provided over 30 years of technical information on the long-term performance of many materials and continues to be upgraded with state-of-the-art capabilities to meet the current and future needs of NASA, other government agencies, and industry for corrosion protection.

With the introduction of the Space Shuttle in 1981, the already highly corrosive conditions at the launch pad were rendered even more severe by the acidic exhaust from the solid rocket boosters. In the years that followed, numerous studies have identified materials, coatings, and maintenance procedures for launch hardware and equipment exposed to the highly corrosive environment at the launch pad.

KSC's Materials Science Laboratories have conducted testing and research in the field of corrosion since 1968. The Corrosion Laboratory was established in 1985 and was outfitted with state-of-the-art equipment to conduct research and materials evaluation in many different corrosive environments. In 2000, the Corrosion Technology Testbed was created in order to achieve KSC's goal of increased participation in research and development.

The Corrosion Technology Testbed is staffed with scientists, corrosion engineers and technicians with extensive experience in the field of corrosion and is outfitted with state-of-the-art instrumentation and equipment to develop new corrosion control technologies and to investigate, evaluate, and determine materials behavior in many different corrosive environments. Its facilities include an Atmospheric Exposure Test Site, documented by the American Society of Materials (ASM) as one of the most corrosive naturally occurring environments in the world, an Electrochemistry Laboratory, a Seawater Immersion System, a Coatings Application Laboratory, and an Accelerated Corrosion Laboratory. The site has recently been outfitted with network connectivity for data acquisition through the Internet.

A historical perspective highlighting the lessons learned in over thirty years of corrosion research, materials evaluation, and development work aimed at protecting and enhancing the safety and reliability of the nation's launch infrastructure and hardware will be presented.

Introduction

The Kennedy Space Center (KSC) is a major source of corrosion expertise. The launch environment at KSC is extremely corrosive due to the combination of ocean salt spray, heat, humidity, and sunlight. With the introduction of the Space Shuttle in 1981, the already highly corrosive conditions at the launch pad were rendered more severe with the acidic exhaust from the Shuttle's solid rocker boosters (SRBs).

Corrosion studies began at KSC in 1966, during the Gemini/Apollo Programs, with the evaluation of long-term protective coatings aimed at protecting the infrastructure at the launch site. NASA/KSC's Beach Corrosion Test Site (BCTS) was established at that time (Figure 1). In the years that followed, numerous studies at the site have identified materials, coatings, and procedures aimed at maintaining the launch hardware and equipment exposed to the highly corrosive environment at the launch pad. Results from these evaluations have helped KSC personnel find new materials and processes that increase the safety and reliability of our launch structures and ground support equipment.

Currently, KSC maintains about $2 billion worth of unique equipment and facilities, not including the four orbiters, valued at about $8 billion. Among the items: two launch complexes, two crawler transporters, three mobile launch platforms, and specialized testing equipment.[1]

Figure 1. KCS's Beach Corrosion Test Site

The BCTS has been documented as having the highest corrosivity of any long-term exposure site in North America.[2] Table 1 compares the corrosivity of the BCTS location with other test sites. The data shows that the corrosivity at KSC exceeds that of the other sites listed. Figure 2 shows the rapid decrease in corrosion rates as distance from the BCTS increases. This illustrates the greatly increased rate of corrosion in the proximity of the launch pads.

The BCTS is located approximately 2 kilometers south of launch complex 39A and is approximately 100 feet from the high tide line of the Atlantic Ocean. The site contains a fully instrumented weather station which provides continuous information on air temperature, humidity, wind direction and speed, rainfall, total incident solar radiation, and incident ultraviolet B radiation levels. The site has approximately 600 feet of front row exposure for atmospheric corrosion specimens. Numerous test samples can be accommodated, including standard size test coupons (4"x 6"), stress corrosion cracking specimens and full-scale articles. Experiments can be performed in either a boldly exposed or sheltered configuration. Both power and data connections are utilized within the site to power test articles and record onboard data instrumentation outputs. The site has recently been outfitted with network connectivity for data acquisition through the Internet. The site has provided over 30 years of technical information on the long-term performance of many materials and continues to be upgraded with state-of-the-art capabilities to meet the current and future needs for corrosion protection of NASA, other government agencies, and industry.

Table 1. Comparison of corrosion rates of carbon steel at various test locations

Location	Type Of Environment	µm/yr	Corrosion rate (a) mils/yr
Esquimalt, Vancouver Island, BC, Canada	Rural marine	13	0.5
Pittsburgh, PA	Industrial	30	1.2
Cleveland, OH	Industrial	38	1.5
Limon Bay, Panama, CZ	Tropical marine	61	2.4
East Chicago, IL	Industrial	84	3.3
Brazos River, TX	Industrial marine	94	3.7
Daytona Beach, FL	Marine	295	11.6
Pont Reyes, CA	Marine	500	19.7
Kure Beach, NC (80 ft. from ocean)	Marine	533	21
Galeta Point Beach, Panama CZ	Marine	686	27
Kennedy Space Center, FL (beach)	Marine	1070	42

(a) Two-year average

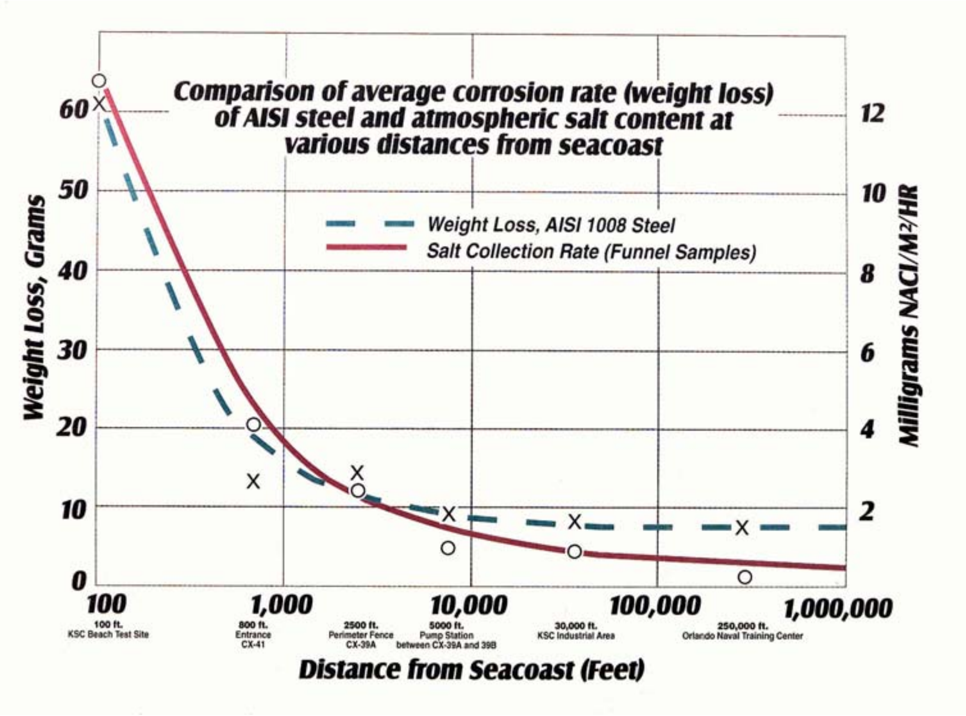

Figure 2. Changes of corrosion rate with distance from the ocean[3]

History of Coating Evaluation and Development at KSC

The testing of coatings aimed at protecting carbon steel, stainless steel, and aluminum has been an ongoing process at KSC for many years. In 1969, a study was initiated to identify coatings for the long-term protection of carbon steel exposed to the seacoast launch environment.[4] Both organic and inorganic zinc-rich coatings were applied to test panels and exposed at the BCTS. These panels were evaluated for corrosion after 18 months, 3 years, 5 years, and 10 years. The results of that study indicated that inorganic zinc-rich primers (ZRPs) were the best choice to provide long-term protection of launch equipment and ground support structures. The inorganic ZRPs outperformed organic zinc in the KSC seacoast environment. In general, topcoats were found to be detrimental to their long-term performance.

Untopcoated inorganic ZRPs were used for many years at KSC for the long-term protection of carbon steel. Several of the original panels exposed in 1969 that were painted with a single coat of ZRP without a topcoat are still showing complete corrosion protection of the carbon steel at the BCTS.[5]

In 1981, the Space Shuttle introduced a more aggressive environment to the launch pads at KSC. Exhaust from the solid rocket boosters (SRBs) resulted in the deposition of small particles of alumina (Al_2O_3) with hydrochloric acid (HCl) adsorbed onto their surface. It is estimated that 17 tons of hydrochloric acid is generated during a Space Shuttle launch. Despite the fact that a pressure wash down was carried out after a launch, the impingement of this exhaust resulted in the failure of the carbon steel corrosion protection provided by the unprotected ZRPs. In response to the SRB exhaust problem, KSC launched a study of new coating systems aimed at resisting this new, more aggressive, environment.

Tests were conducted in 1982 and 1986 to identify topcoats to enhance the chemical resistance of the coating systems in use at KSC. The 1982 study determined that 2-component coatings were far superior to single-component types, epoxy/urethane topcoats provided some protection to the ZRPs, and repair techniques, other than abrasive blasting, were ineffective in the launch environment.[6] The 1986 study focused on higher-built topcoat products to improve chemical resistance. As a result of this study, 10 topcoat systems were approved for use in the Space Shuttle Launch environment.[7]

All the coating systems, selected as a result of the aforementioned studies, utilized solvent-based inorganic ZRPs top coated with a variety of systems. In general, the topcoat systems that proved successful in the 1986 study contained epoxy mid-coats followed by polyurethane topcoats. All topcoat systems were solvent thinned. The results of these programs provided valuable data and resulted in the selection of appropriate coatings for the protection of KSC structures in their uniquely aggressive marine and chemical environment. However, Clean Air legislation and environmental regulations began to restrict the use of solvents in paints and coatings. These regulatory developments indicated that all inorganic ZRPs and topcoat systems approved for use at KSC would eventually need replacement.

To address this challenge, studies were undertaken in 1990, and are being continued to this day, to identify inorganic ZRPs and topcoat systems that would provide superior protection while complying with the anticipated strengthening of environmental quality standards.[8,9] Many of the coating systems tested, started with water-based inorganic ZRPs followed by water-based acrylic topcoats resulting in protective coating systems with essentially zero volatile organic compounds (VOCs). This prospect would not only allow compliance with air quality regulations, but would also significantly reduce the use of flammable solvents and associated hazardous waste. In addition to liquid applied coatings, several powder-coating materials were evaluated for corrosion protection performance.

In an effort to reduce the time spent refurbishing facilities between launches, sprayable silicone ablative coatings were investigated as a replacement for the ceramic-filled epoxy coatings in use. Previous ablative materials were ceramic-filled epoxies developed in the 1960s for the manned space flight programs. A 1994 investigation determined that sprayable silicone ablative coatings provided excellent heat and blast protection for launch structures.[10]. The sprayable silicone ablative coatings were developed in response to concerns about damage to the protective tiles used on the Space Shuttle. The potential for damage resulted from the tendency of the ceramic-filled epoxy ablatives to spall when subjected to the thermal, impact, and pressure stresses involved in the exhaust plume of SRBs. In addition to the improved performance characteristics, sprayable silicone ablatives can be applied by plural component spray over inorganic ZRPs. This results in a significantly higher rate of production than possible with the ceramic-filled epoxies. Ceramic-filled epoxy application requires labor-intensive mixing of a three-component system and manual application to a substrate primed with the epoxy components (without the ceramic filler). The use of sprayable silicone ablative coatings decreased the time required to refurbish the umbilical tower and other affected areas in preparation for subsequent launches. As a result, shuttle contractors installed the ablative material at Launch Complex 39B (LC39B) in 1994 on the entire 95' level, and on camera and communication boxes as well. A project is currently underway to apply these materials to the Mobil Launch Platforms (MLPs) to reduce launch damage. Development work shows that hold down post blast shields are candidates for silicone protection.

Recent research has concentrated on the development and evaluation of conductive polymer coatings,[11] polisiloxane coatings,[12] silicone coatings for blast and heat protection of launch structures,[13] and molybdate conversion coatings[14] as a possible replacement for chromium conversion coatings.

In the mid 1980s, researchers at KSC became interested in polyanylines (PANs) as protective coatings for metallic surfaces. As it was mentioned previously, during the previous 20 years, extensive coating testing at KSC had lead to the conclusion that inorganic ZRPs significantly outperformed organic zinc-rich type primers in the marine atmosphere of Florida. This was partially attributed to the increased conductivity of the inorganic ZRP coating film. The materials typically used to make the organic zinc-rich films (e.g., epoxies, vinyls, etc.) produced an undesirable insulating effect on the zinc particles. This effect resulted in decreased galvanic activity of the zinc particles in protecting the carbon steel substrate. On the other hand, the organic zinc-rich primers had the advantage of protecting the steel under conditions of less than perfect surface preparation. The organic polymers provided better adhesion to marginally prepared substrates than the inorganic materials. This result led researchers at KSC to consider the use of conductive organic materials to formulate these zinc coatings providing the best of both worlds. The idea being that the conductive organic vehicle would provide both the increased conductivity needed for superior galvanic protection of the steel substrate and would allow better adhesion with less than perfect surface preparation. Hence the work on conductive organic polymers and the search for materials that would allow the production of a new generation of protective coatings based on this technology began.

The Department of Energy's Los Alamos National Laboratory (LANL) awarded the 1997 Distinguished Patent Award to a team that included two KSC chemists. The patent (U.S. Patent 5,658,649), entitled Corrosion Resistant Coating, was selected as the top patent from the 41 issued at LANL in 1997. The formula for the coating features PAN as its active ingredient.

A collaboration between NASA/KSC and the University of Arkansas resulted in the development of a water and solvent soluble coating additive. The Ligno Sulfonic Acid Doped Polyaniline (Ligno-Pani) is being commercialized by an Ohio Company under NASA license. The technology offers several advantages, including the use of inexpensive materials, such as aniline and lignin. Lignin is a paper and pulp manufacturing waste product. Unlike existing coatings and systems used for corrosion prevention, Ligno-Pani does not utilize ozone-depleting VOCs or heavy metals that pollute the water supply.[15]

A program was initiated in 1994 to identify alternative inorganic topcoat materials for use at KSC and to study the performance of a new high-gloss polysiloxane topcoat for inorganic ZRPs. Evaluation of the coated panels at the 18-month exposure period provided information for the revision of approved coating systems at KSC.

Thin gauge stainless steel and aluminum structures, such as protective bellows around drive mechanisms, flex repeatedly and thus require highly flexible and adherent coatings. The aerospace industry has traditionally used paints having high VOC contents for protecting vehicles and launch support structures. Flexible paints employ highly solvated rubber binder resins, which render the products highly volatile and difficult to apply by spraying. Silicone-based paints are formulated to yield temperature- and weather-resistant coatings while at the same time prevent corrosion by forming effective electrolyte barriers. However, silicones are normally delivered from organic solvents and exhibit poor adhesion to unprimed metals.

Experimental VOC-compliant primerless silicone coatings for corrosion control were developed by an industry partner for NASA/KSC under a Small Business Innovation Research (SBIR) contract. The ultimate goal in developing the coatings is to provide an effective, environmentally sound method to protect the surface of aluminum and stainless steel without introducing additional pretreatment and priming steps. The waterborne elastomeric anticorrosion coatings being developed consist of aqueous dispersions of silicone resins, stabilized with polymeric surfactants and pigmented with non-toxic anticorrosive additives. The latter silicone-modified polymers yield emulsions that adhere the coating to metal surfaces. By forming a topcoat-bound primer layer *in situ*, a coating with low VOC content and having simple application properties can be formulated.

An environmentally friendly molybdate-based conversion coating for aluminum and aluminum alloys resulted from a collaboration between an industry partner and NASA under another SBIR contract. The innovation, referred to as “Molyseal,” is a significant development since it contains molybdate instead of chromate. The molybdate conversion coating does not contain chemicals that are harmful to the environment or to humans and it was developed as a possible substitute for chromium conversion coatings. Chromate conversion coatings have been used for the protection of aluminum alloys for over 70 years. Although their efficiency in minimizing corrosion attack is excellent, there are health and safety concerns over their use due to their toxicity and carcinogenic nature. NASA/KSC has used chromate-based coatings on many of its spacecraft and desires to replace them with safer coatings. Despite an extensive research effort over the past decade, a completely satisfactory replacement for chromate conversions coatings has yet to be identified. Though preliminary tests demonstrated an exceptional corrosion protection by the new Molyseal coating. These results established a sound technical feasibility for this new molybdate conversion coating.[16]

Corrosion Performance of Alloys in the Space Shuttle Launch Environment

KSC's Materials Science Laboratories have conducted testing and evaluation of the corrosion behavior and corrosion protective properties of different materials in the Space Shuttle Launch Environment since 1968. The Corrosion Laboratory (established in 1985) was outfitted with state-of-the-art electrochemistry equipment to conduct research and characterize materials in many different corrosive environments.

In 1987, a study was initiated to find a replacement alloy for the 304 stainless steel in the metal flex hoses used in various supply lines that service the Orbiter at the launch pad. These convoluted flexible hoses which were originally made out of 304L stainless steel had failed due to pitting. In the case of vacuum jacketed cryogenic lines, pinhole leaks, caused by failure of the flex hose, produced a loss of vacuum and subsequent loss of insulation. 19 alloys were investigated and evaluated using a variety of techniques that included exposure at the BCTS, electrochemical characterization, Salt Fog Chamber Exposure, and Ferric Chloride Immersion. As a result of that study, a nickel-chromium-molybdenum-tungsten substitute alloy was identified to replace the 304 stainless steel in use. Flex hoses made of this alloy are now performing without failure due to corrosion at the launch pad since 1988.[17]

A current investigation is underway to study the behavior of eleven corrosion resistant alloys to replace the 304L stainless steel tubing at the Space Shuttle launch sites. The eleven alloys include 317L, 316L, 2205, C-276, and 625, 254 SMO, C-2000, AL-6XN, AL29-4C, and 2507. The first five were part of the previous investigation. Since 304 stainless steel tubing is susceptible to pitting corrosion and Stress Corrosion Cracking (SCC), .using corrosion resistant tubing utilizing a more suitable corrosion resistance alloy will greatly reduce the probability of future failures. These advancements will result in improved safety and reduced maintenance costs at the launch site.

In 2000, the Corrosion Technology Testbed was created in order to achieve KSC's goal of increased participation in research and development. The Corrosion Technology Testbed is staffed with scientists, corrosion engineers and technicians with extensive experience in the field of corrosion and is outfitted with state-of-the-art instrumentation and equipment to develop new corrosion control technologies and to investigate, evaluate, and determine materials behavior in many different corrosion environments. Its facilities include an Atmospheric Exposure Test Site, an Electrochemistry Laboratory, a Seawater Immersion System, a Coatings Application Laboratory, and an Accelerated Corrosion Laboratory.

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