National Aeronautics and Space Administration

NASA's Corrosion Technology Laboratory at the Kennedy Space Center: Anticipating, Managing, and Preventing Corrosion

2014 INTERNATIONAL WORKSHOP ON ENVIRONMENT AND ALTERNATIVE ENERGY
"Increasing Space Mission Resiliency through Sustainability"

October 21-24, 2014

Kennedy Space Center, FL, USA

Luz Marina Calle, Ph.D.
NASA's Corrosion Technology Laboratory
Kennedy Space Center, FL, 32899, USA

Outline

- Introduction
- Corrosion
  - Definition, impact, and cost
  - Corrosion grand challenges; coatings pollution
  - Natural and Launch environments at NASA's Kennedy Space Center (KSC)
  - Corrosion at KSC
  - Qualifying coatings for NASA's launch facilities
  - Computerized corrosion management at KSC
  - NASA's Corrosion Technology Laboratory Website
- Corrosion evaluation
  - Atmospheric exposure testing
  - Accelerated tests
  - Electrochemical measurements
  - Surface analysis
- Corrosion Engineering Projects
  - Environmentally driven projects
- Technology Development
  - Smart coatings
  - Environmentally friendly corrosion protective compounds (CPCs)
  - New accelerated corrosion test method

Introduction

- NASA has been dealing with corrosion since the inception of the Space Program in 1962 because it launches from the most naturally corrosive environment in North America
- The beachside atmospheric exposure test site was established in 1966 to test materials coatings, and maintenance procedures near the launch pads
- In 1981, corrosion conditions at the launch pads became even more severe due to solid rocket booster (SRB) exhaust products from the Space Shuttle
- In 1985, electrochemical corrosion testing begins
- In 2000, The Corrosion Technology Laboratory is created to achieve KSC's goal of increased participation in research and development
- In 2000 a computerized corrosion data management system is implemented
- In 2001, NASA Technical Standard NASA-STD-5008 for Protective Coatings of Carbon Steel, Stainless Steel, and Aluminum on Launch Structures, Facilities, and Ground Support Equipment is approved
- In 2004, the corrosion technology laboratory starts developing smart coatings based on microencapsulation technology specifically designed for corrosion control applications (U.S. Patents No. 7,790,225, 2010 and 20130017612).

Introduction

- In 2011, NASA-STD-5008B revision updates the standard and adds a paragraph on environmental stewardship:

  a. Environmental, health, and safety impacts of processes and materials shall be taken into account when employing protective coating methods and techniques.

  b. Alternative, environmentally friendly materials that do not contain hexavalent chromium, lead, cadmium, or hazardous air pollutants (HAPs), such as methyl ethyl ketone, toluene, and xylene, shall be considered when determining the correct coating method/technique for each protective coating application.

- 2014, NASA's Space Technology Roadmap includes corrosion control technologies as one of the areas needed to lower the cost and improve the sustainability and efficiency of its ground operations in support of future launch activities.
- This presentation provides a chronological overview of NASA's Corrosion Technology Laboratory at the Kennedy Space Center role in anticipating, managing, and preventing corrosion throughout the history of NASA's Space Program

What is Corrosion?

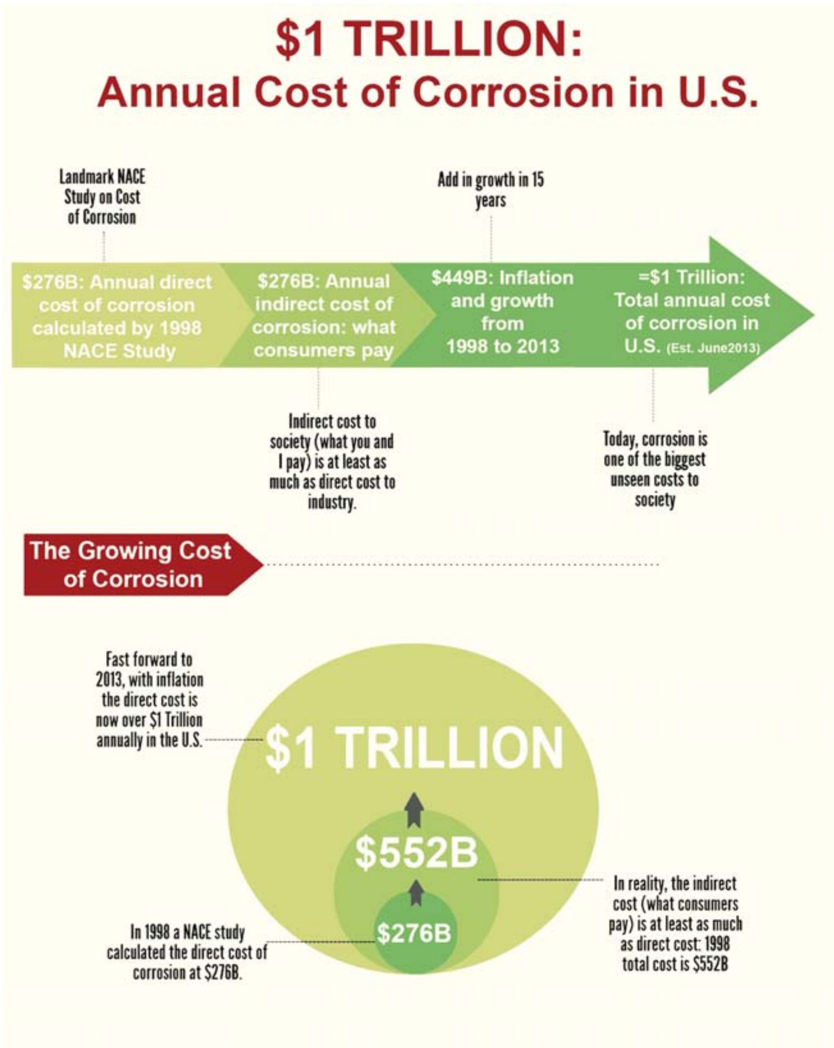
- Corrosion is the deterioration of a material due to reaction with its environment (M.G. Fontana). It literally means to "gnaw away"
- Degradation implies deterioration of the properties of the material.

KSC Crawler/Transporter
Structural Steel Corrosion

Impact of Corrosion

Research Opportunities in Science and Engineering, Committee on Research Opportunities in Corrosion Science and Engineering; National Research Council, The National Academies Press, 2011

Cost of Corrosion



- **At US $2.2 (1.6 €) trillion, the annual direct cost of corrosion worldwide is over 3% of the world's GDP.***
- **Direct costs do not include the environmental damage, waste of resources, loss of production, or personal injury.**

Gross Domestic Product - GDP The monetary value of all the finished goods and services produced within a country's borders in a specific time period, though **GDP** is usually calculated on an annual basis.

*World Corrosion Organization 2010

(1 Trillion = 10^{12} = 1 billion)

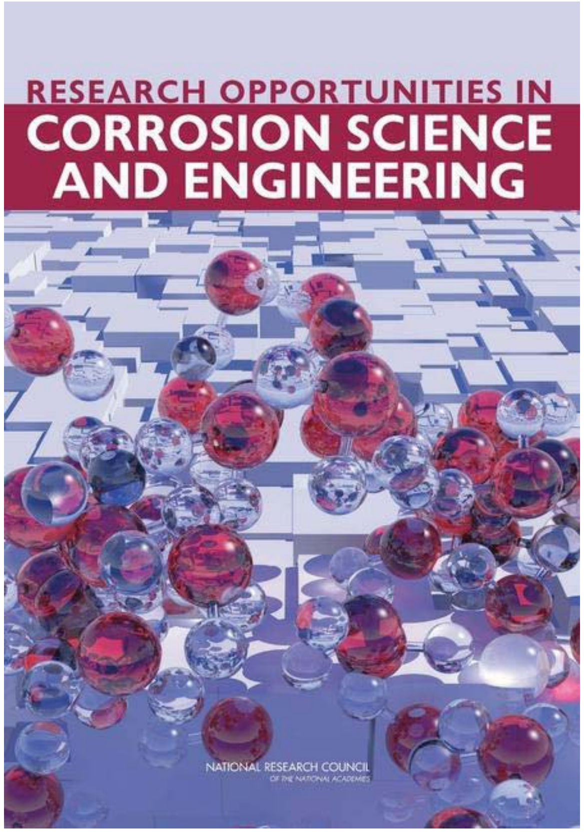
Cost of Corrosion Control at KSC

Cost of corrosion control at KSC Launch Pads estimated as $1.6M/year[1]

[1] Estimate based on corrosion control cost of launch pads (39A and 39B) and the 3 Mobile Launch Platforms (MLPs) in 2001

Corrosion Grand Challenges*

- **Development of cost-effective, environment-friendly, corrosion-resistant materials and coatings.**
- **High-fidelity modeling for the prediction of corrosion degradation in actual service environments.**
- **Accelerated corrosion testing under controlled laboratory conditions. Such testing would quantitatively correlate with the long-term behavior observed in service environments.**
- **Accurate forecasting of remaining service time until major repair, replacement, or overhaul becomes necessary. i.e., corrosion prognosis.**



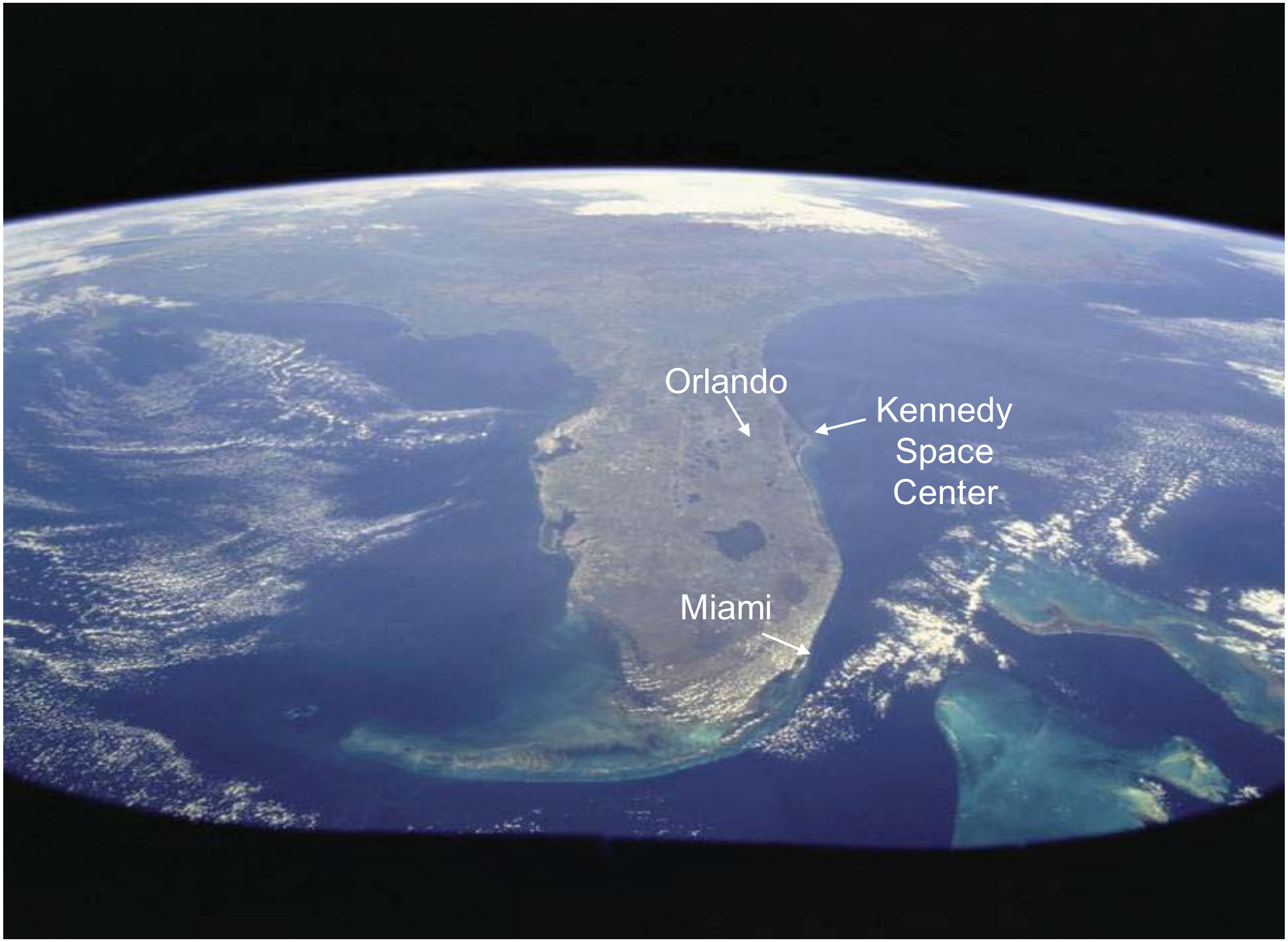
***Research Opportunities in Corrosion Science and Engineering,** Committee on Research Opportunities in Corrosion Science and Engineering; National Research Council (2010)99

Coatings Pollution

- Surface Preparation or Cleaning
  - Pretreatment, solvents, conversion coatings
- Coating Application Process
  - Type of process: spray, roller coating, electrocoat
  - Type of coating: high VOC, toxic pigments (hexavalent chromium)
  - Waste: leftover paint, cleaning solvents/thinners, Air emissions (VOCs & HAPs), Spray booth filters, Soiled rags, Expired shelf-life inventory
- Coating removal
  - Waste (may be toxic)

VOC: Volatile Organic Compound; HAP: Hazardous Air Pollutants

Where Are We?



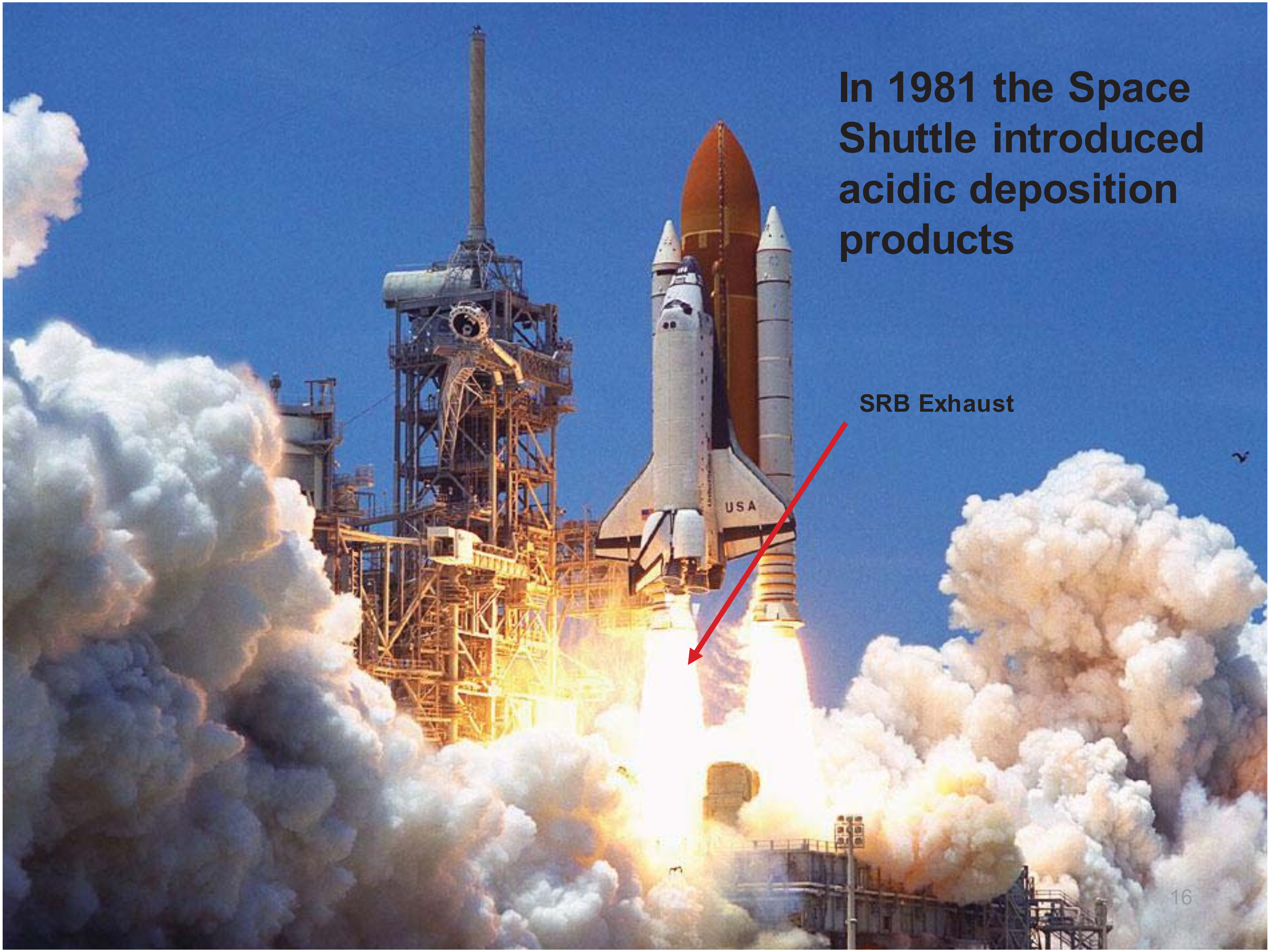

The Kennedy Space Center in Florida, USA, is a special place where we launch rockets from a wild life refuge in one of the most corrosive areas in the world
Rod Ostoski

KSC Natural Environment

KSC Launch Environment

KSC Launch Environment

Positioned within 1,000 ft (305 m) of the Atlantic Ocean, KSC's launch facilities are exposed to salty air that blows from the ocean, high ambient air temperatures, and an extensive amount of UV Light. The high temperature of the engine exhaust is up to nearly 5,000 F (2,760 °C). Close to 70 tons of hydrochloric acid (HCl) are generated by the combustion products a rocket's solid propellant.


In 1981 the Space Shuttle introduced acidic deposition products
SRB Exhaust
USA

Natural Salt Fog Chamber

Corrosion Rates of Carbon Steel

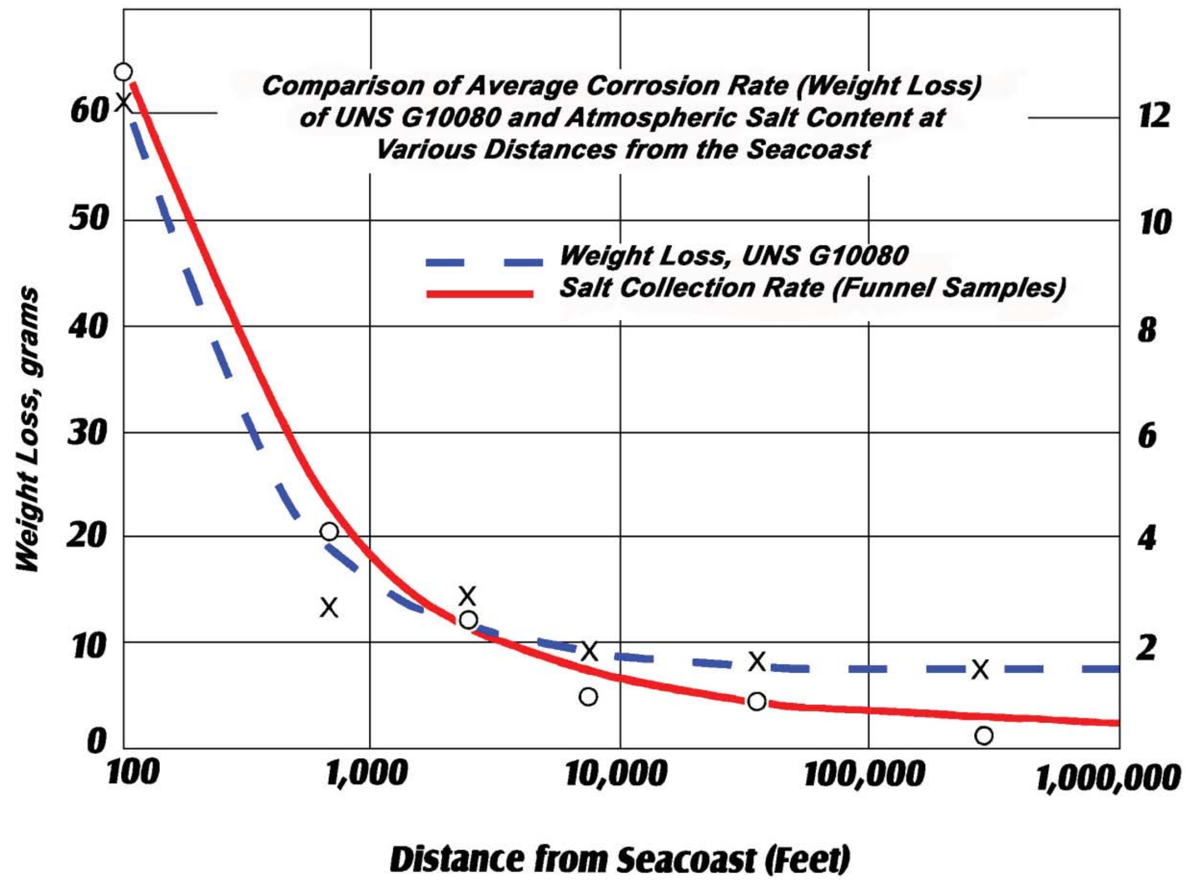
Corrosion rates of carbon steel calibrating specimens at various locations*			
Location	Type Of Environment	µm/yr	Corrosion rate[a] mils/yr
Esquimalt, Vancouver Island, BC, Canada	Rural marine	13	0.5
Pittsburgh, PA	Industrial	30	1.2
Cleveland, OH	Industrial	38	1.5
Limon Bay, Panama, CZ	Tropical marine	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	21.0
Galeta Point Beach, Panama CZ	Marine	686	27.0
Kennedy Space Center, FL (beach)	*Marine*	*1070*	*42.0*

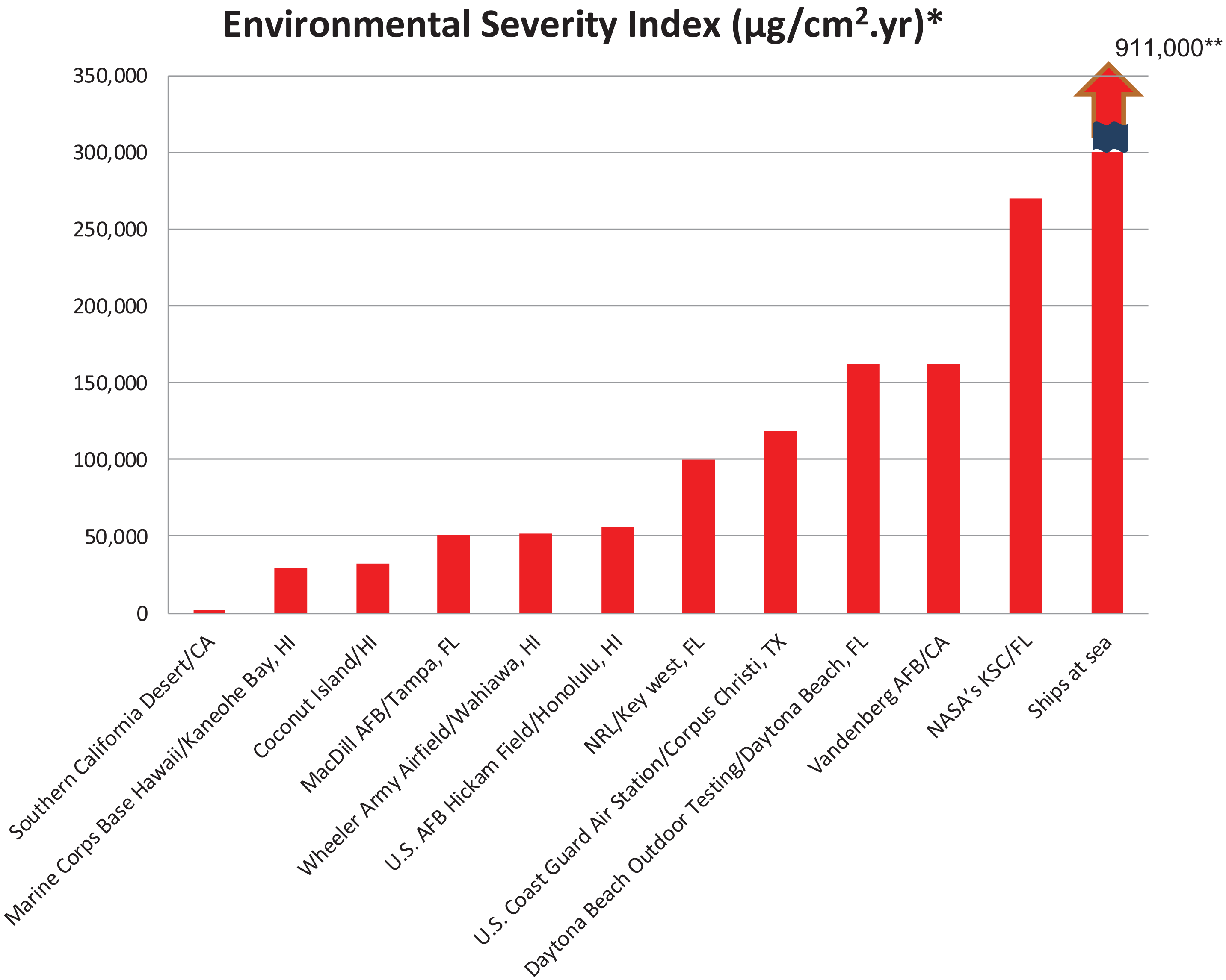
[a]Two-year average

* Data extracted from: S. Coburn, Atmospheric Corrosion, in Metals Handbook, 9th ed, Vol. 1, Properties and Selection, Carbon Steels, American Society for Metals, Metals Park, Ohio, 1978, p.720

A mil is one thousandth of an inch

Changes In Corrosion Rate with Distance From The Ocean





*Corrosion Comprehension: Operating in a Corrosive Environment, DoD Video, March 2012. DoD established an Environmental Severity Index (ESI) derived from 10 years of observations of steel and aluminum alloy samples (or "coupons") left exposed to the elements at 130 military installations around the world.

Determined experimentally using an **Alternating Seawater Spray System at NASA's Beachside Corrosion Test Site at KSC.

Examples of Launch Pad Corrosion

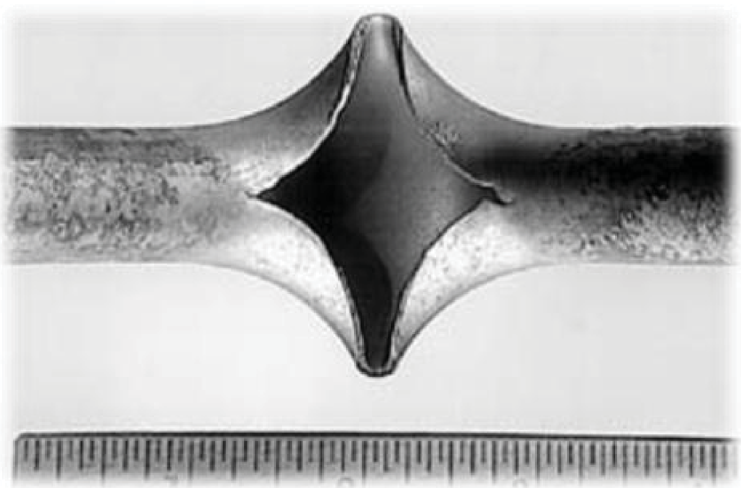
Enclosed / Inaccessible Areas

Dissimilar Metals

KSC Launch tower structural steel corrosion

Under the LC 39B Flame Trench

Corrosion Failures



Tubing split caused by Pitting

Hidden corrosion

Corrosion Evaluation Studies at KSC

- Corrosion evaluation studies began at KSC in 1966 during the Gemini/Apollo Programs.
- The KSC Beachside Corrosion Test Site was established at that time to conduct controlled corrosion studies for protective coatings.

Saturn V

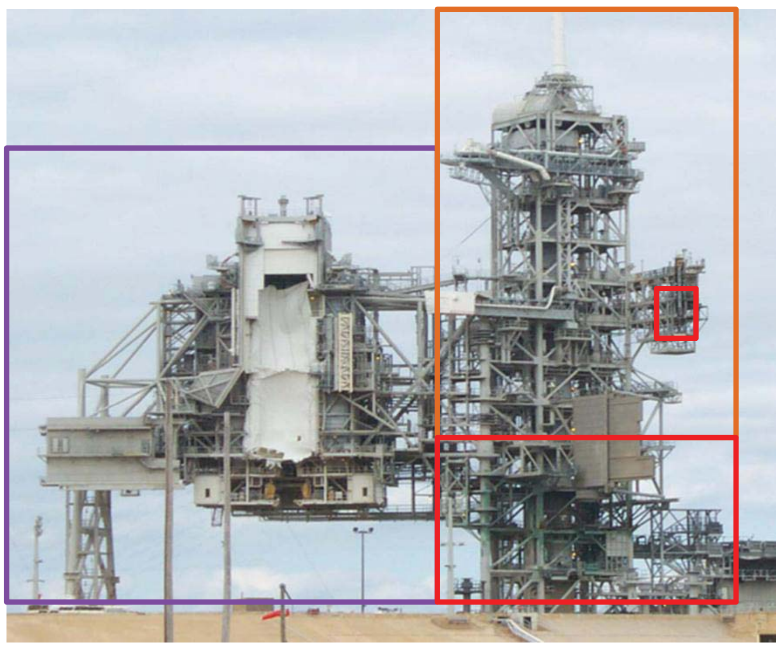
Qualifying Coatings for NASA Launch Facilities

- Over the years, the Corrosion Technology Laboratory has developed proven methodologies to evaluate and test materials and coatings for use in NASA's unique corrosive environments
- Based upon this knowledge, experience and expertise, NASA-STD-5008B, "Protective Coating of Carbon Steel, Stainless Steel, and Aluminum on Launch Structures, Facilities, and Ground Support Equipment" was developed to test and evaluate protective coatings to control corrosion of these assets.

NASA-STD-5008B

Specification NASA-STD-5008B *Protective Coating of Carbon Steel, Stainless Steel, and Aluminum on Launch Structures, Facilities, and Ground Support Equipment*

- Governs maintenance at John F. Kennedy Space Center and other NASA Centers.
- Establishes practices for the protective coating of ground support equipment and related facilities.
- Zones of Exposure are established to define coating system Requirements for specific environments.



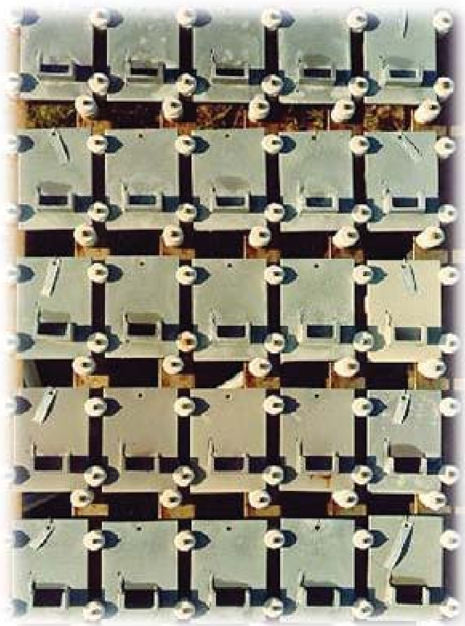
Launch complex 39 zones of exposure

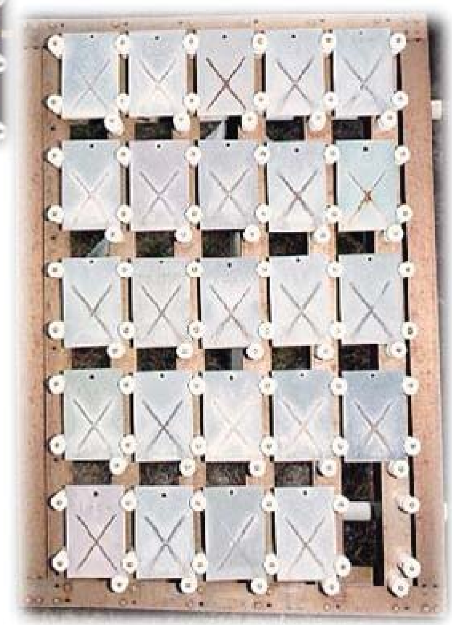
NASA-STD-5008B

- In order for a coating system to be used at NASA it must be listed on the NASA-STD-5008B Approved Products List. Coating systems on this list are qualified according to the requirements of NASA-STD-5008B by the Corrosion Technology Laboratory.
- Typical protocol requires laboratory adhesion tests, color measurements, gloss measurements, and corrosion evaluations on the coatings exposed at the NASA KSC Beachside Corrosion Test Site

Atmospheric Exposure

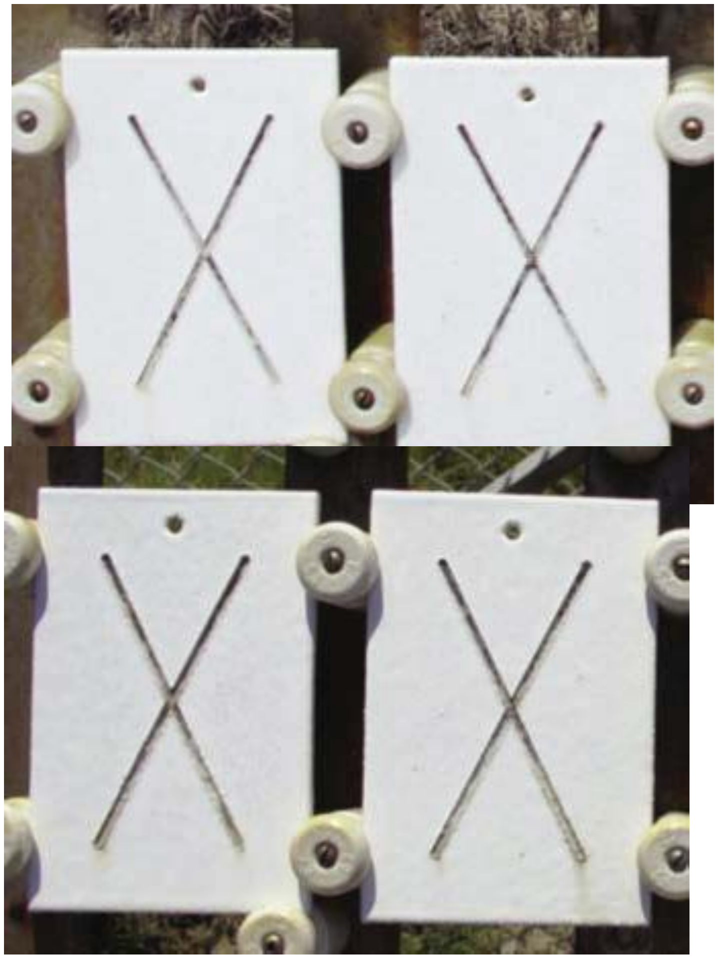
Real world exposure at a site that mimics actual performance requirements



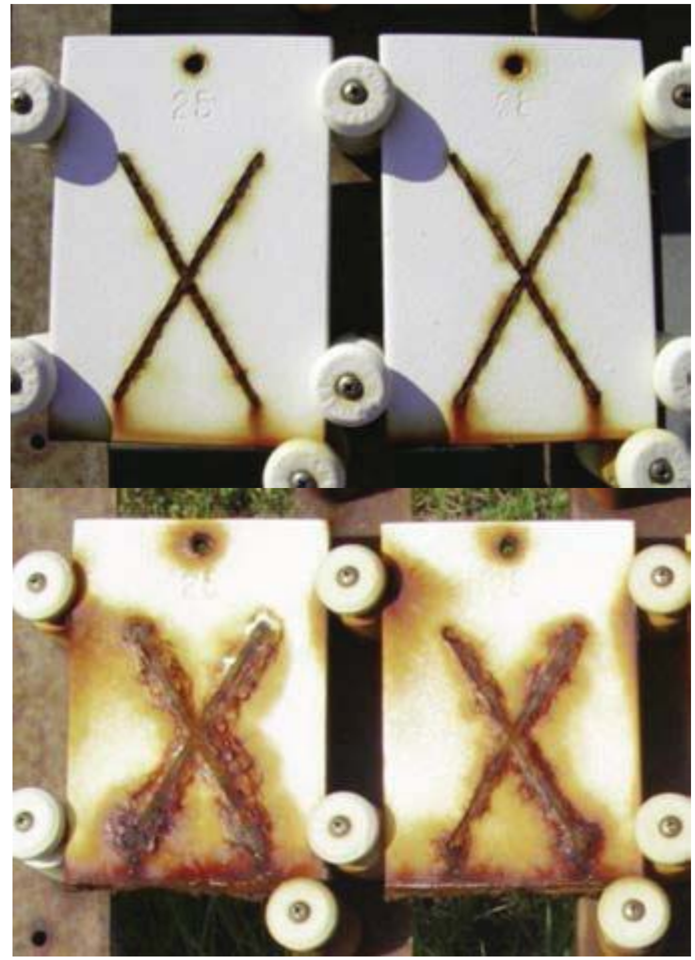


NASA Technical Standard for Protective Coatings (NASA-STD-5008B) requires 18 months of good performance for preliminary approval and continued good performance for 5 years for final approval of a coating system.

Coatings Qualification



Coating samples at 18 months (top) and 60 months (bottom) of exposure. This coating was approved for use.

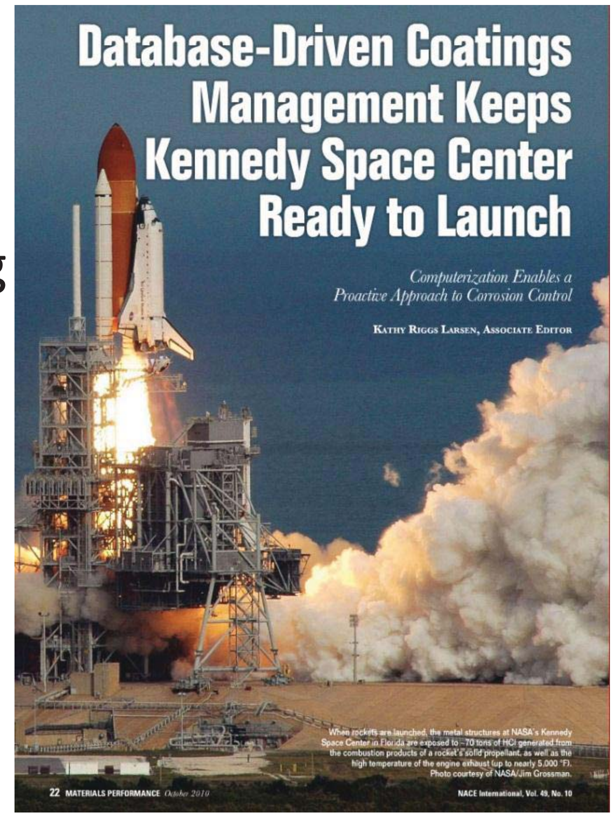


Coating samples at 18 months (top) and 60 months (bottom) of exposure. This coating was not approved for use

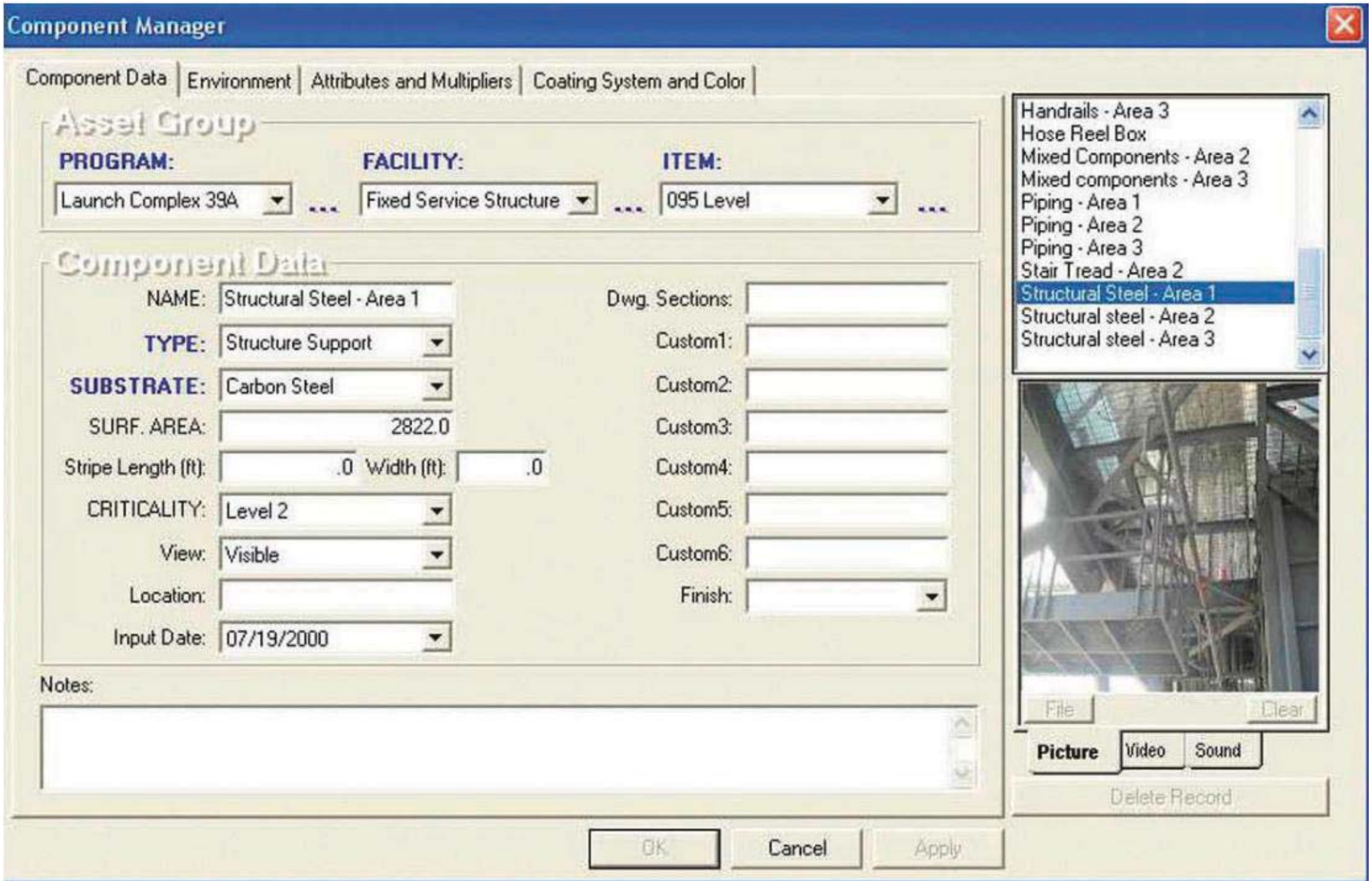
Computerized Corrosion Management

Since 2000, a computerized corrosion management program has been used to keep track of corrosion in more than 3,600 critical components and 7-8 million ft^2 of surface area.

- Launch complex components
  - Launch towers and structures
  - Sound suppression water systems
  - Cryogenic fuel tanks and associated piping
  - Access towers
  - High-pressure gas tanks
  - Camera towers
  - Lighting protection
  - Mobile launch platforms
- Metallic structures outside launch area



Computerized Corrosion Management



Information stored in the database includes the location of the structure, the type of structure, the surface area of the structure, the substrate material, and the current condition of the coating system. Photos visually document condition ratings

Computerized Corrosion Management

This series of photos tracks how corrosion of a water pipe at KSC's launch complex 39B has progressed over four years

NASA's Corrosion Technology Laboratory Website

Corrosion Technology Laboratory

Site Map

Home | Facilities | Coatings | Corrosion Fundamentals | Resources | Customers | KSC Home Page

The Corrosion Technology Laboratory at the NASA Kennedy Space Center is a network of capabilities – people, equipment, and facilities that provide technical innovations and engineering services in all areas of corrosion for NASA and external customers.

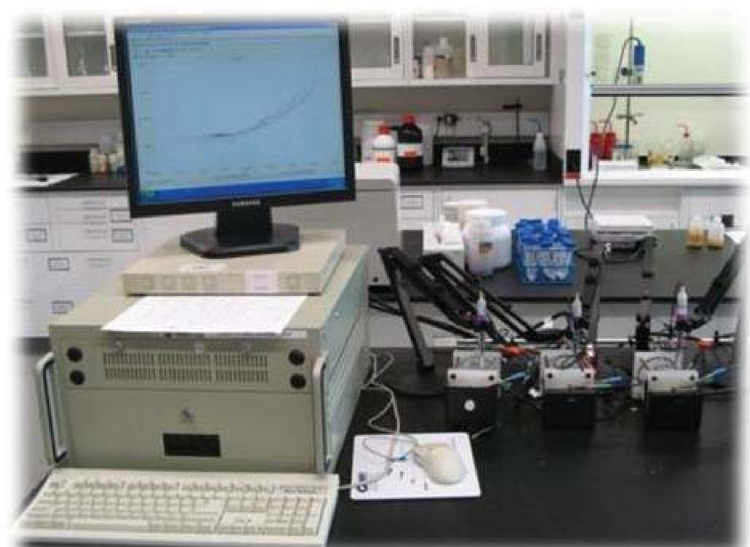
The Corrosion Technology Laboratory:

- Provides consulting and testing services for NASA and external customers
- Conducts applied research
- Develops new corrosion detection and control technologies
- Investigates, evaluates, and determines materials performance and degradation in different environments in support of NASA, other government organizations, industry, and educational institutions
- Participates in educational outreach activities

http://corrosion.ksc.nasa.gov/

Corrosion Evaluation at KSC (current)

- Field Exposure
- Accelerated testing
- Electrochemical testing
- Technology development



KSC Beachside Corrosion Test Site

NASA's Corrosion Technology Laboratory

The Corrosion Technology Laboratory at NASA's Kennedy Space Center provides technical innovations and engineering services in all areas of corrosion/materials degradation for NASA and external customers.

Capabilities

- **Beachside Atmospheric Exposure**
- **Full Seawater Immersion Exposure**
- **Tidal Exposure**
- **Seawater Spray/Splash (Splash Zone) Exposure**
- **Corrosion Engineering Services**
- **Accelerated Corrosion Testing**
- **Concrete Testing**
- **Cathodic Protection**
- **Coating Development**
- **Electrochemistry**
- **Surface Analysis**
- **Coating Application and Evaluation**
- **Website:** http://corrosion.ksc.nasa.gov/

Beachside Corrosion Test Site

Seawater Spray/Splash Exposure (Simulated Shipboard Testing)

Environmentally Driven Projects

- Non-Chrome Systems Testing
- Hexavalent Chrome Free Coatings for Electronics
- Alternative to Nitric Acid Passivation
- Environmentally Preferable Coatings for Structural Steel (Launch Structures)
- NASA- STD -5008B Protective Coating of Carbon Steel, Stainless Steel, and Aluminum on Launch Structures, Facilities, and Ground Support Equipment
- Low VOC Topcoats for Thermal Spray Coatings
- Environmentally Friendly Corrosion Protective Compounds (CPCs)
- Smart and Multifunctional Corrosion Protective Coating Development

Alternative to Nitric Acid Passivation

Expected Results
- Provide the data necessary to verify that citric acid can be used as an environmentally preferable alternative to nitric acid for passivation of stainless steel

Benefits of Citric Acid
- Citric acid does not remove nickel, chromium, and other heavy metals from alloy surfaces
- Reduced risk associated with worker health and safety
- Reduced hazardous waste generation resulting in reduced waste disposal costs
- Reduced Nitrogen Oxide (NOx) emissions that are a greenhouse gas, contribute to acid rain and smog, and increased nitrogen loading (oxygen depletion) in bodies of water

Image: Master isolated images / FreeDigitalPhotos.net

Smart Coatings for Corrosion Control

- The use of "smart coatings" for corrosion sensing and control relies on the changes that occur when a material degrades as a result of its interaction with a corrosive environment.
- Such transformations can be used for detecting and repairing corrosion damage.
- The Corrosion Technology Laboratory is developing a coating that can detect and repair corrosion at an early stage.
- This coating is being developed using pH sensitive microcontainers that deliver their contents when corrosion starts to:
  - Detect and indicate the corrosion location
  - Deliver environmentally friendly corrosion inhibitors
  - Deliver healing agents to repair mechanical coating damage.

http://upload.wikimedia.org/wikipedia/commons/1/12/Cape_Dwarf_Chameleon.jpg

Microencapsulation-based Smart Coatings

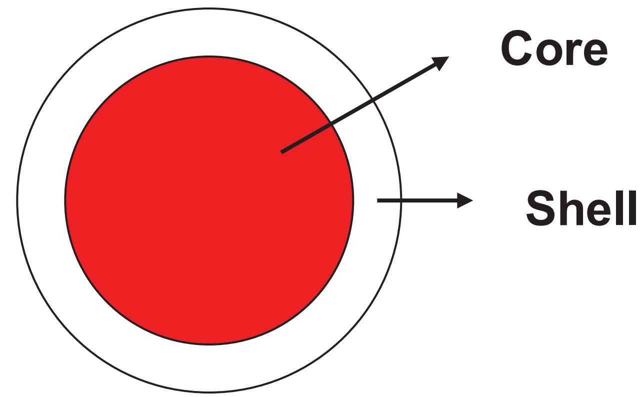
Corrosion indication, detection, and healing of mechanical damage can be achieved using microencapsulation technology

What are microcontainers?

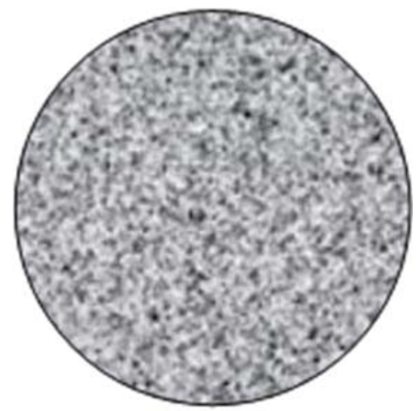
Particles or liquid drops coated in polymers. These microcontainers can carry any material that needs protection or controlled release.

Why microencapsulate a material?

- Incorporate active materials while maintaining coating integrity
- Achieve controlled-release
- Make active materials easier/safer to handle.
- Incorporate multiple component systems.
- Prevent undesired leaching
- Versatility



Microcapsules



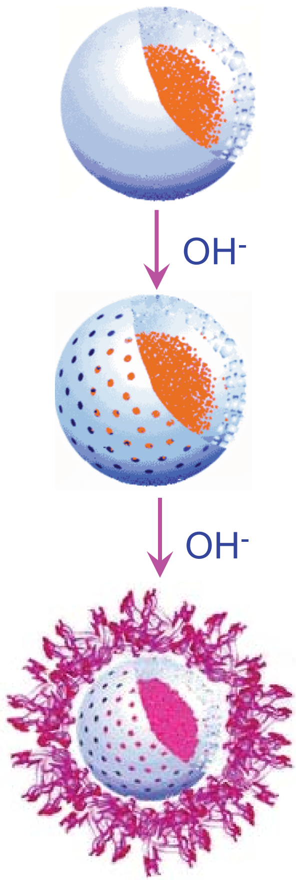
Microparticles

Types of Feedback-Active Microcontainers for Corrosion Detection and Control

- Containers with an active ingredient-rich core and stimuli-responsive shell (microcapsules)
- Containers with an active ingredient incorporated into a stimuli-responsive matrix (microparticles)
- Containers with a porous ceramic core impregnated by inhibitor and enveloped by a stimuli-responsive polyelectrolyte (PE) shell*

*D. Grigoriev, D. Akcakayiran, M. Schenderlein, and D. Shcukin, Corrosion, 70

pH-triggered Release Microcapsules

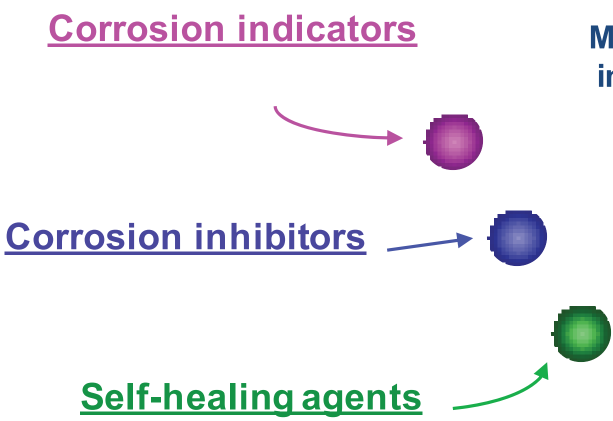


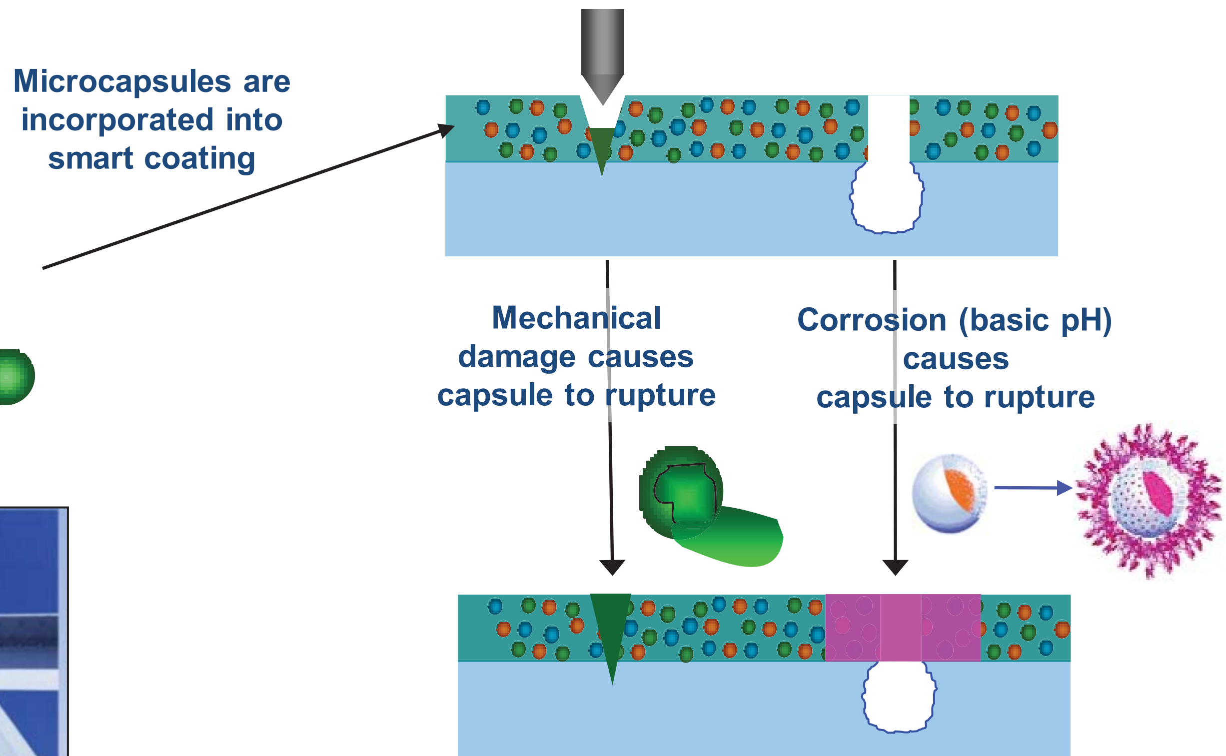
Microcapsule containing pH indicator (inhibitor, self healing agents)

The shell of the microcapsule breaks down under basic pH (corrosion) conditions

pH indicator changes color and is released from the microcapsule when corrosion starts

Smart Coating Response to Corrosion and Mechanical Damage





Environmentally Friendly Corrosion Protective Coatings And Corrosion Preventative Compounds (CPCs)

- Progressively stricter environmental regulations are driving the coating industry to abolish many corrosion protective coatings and corrosion preventative compounds (CPCs) that are not environmentally friendly.

- The objective of this project is to identify, test, and develop qualification criteria for environmentally friendly corrosion protective coatings and corrosion preventative compounds (CPCs) for flight hardware and ground support equipment .

Dead tree/fish label warnings required in Europe for zinc primers

Harmful to aquatic organisms, may cause long-term adverse effects in the aquatic environment. (Europe MSDS))

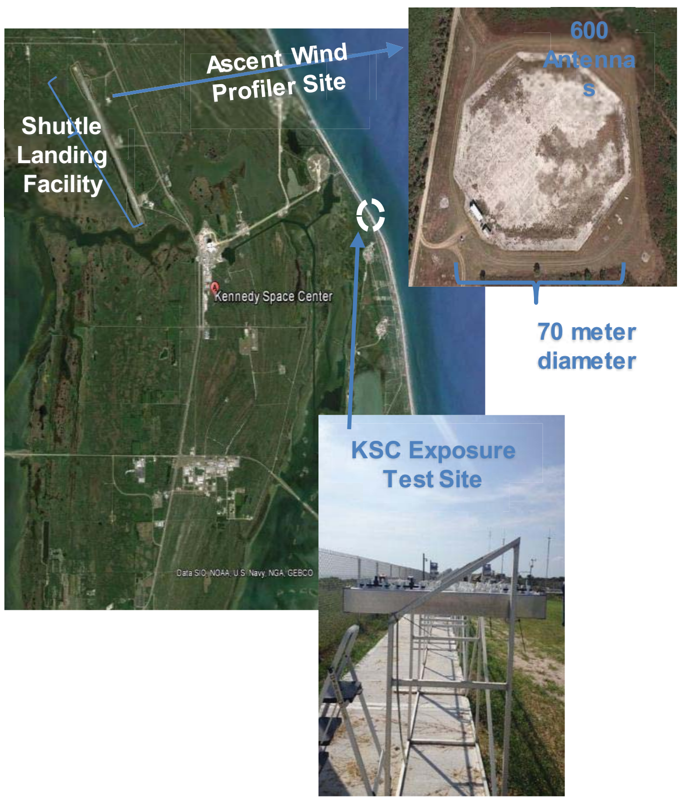
Keep out of waterways. (US MSDS)

Corrosion Preventive Compounds (CPCs)

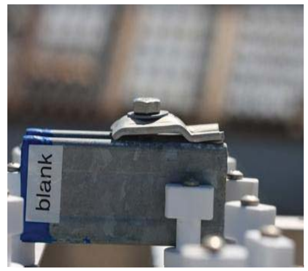
Example: Ascent Wind Profiler, World's Largest Doppler Radar Site

Located at the north side of the NASA KSC Shuttle Landing Facility

Areas of Dissimilar Metal and Crevice Corrosion



Corrosion Testing

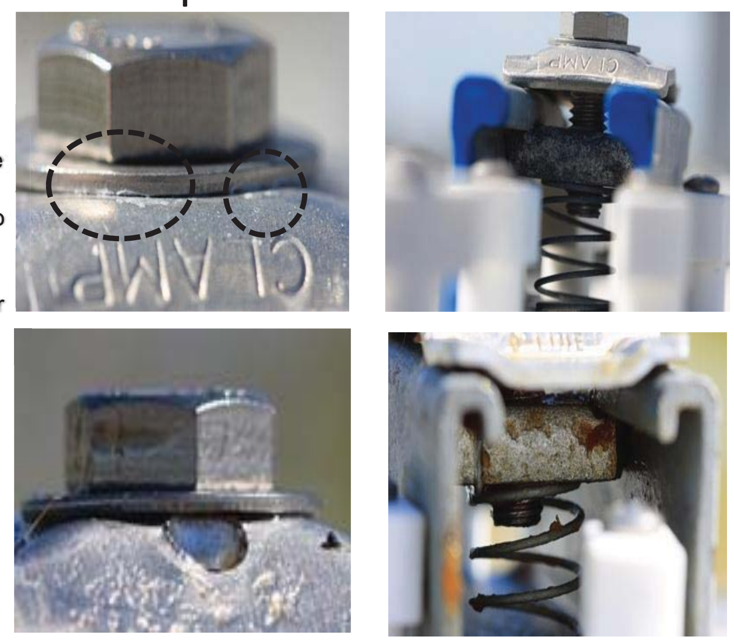


Example cable clamp test article

CPCs offer a viable solution that can be easily incorporated into the current work constraints (ease of application and reapplication schedule)

Initial salt fog chamber results

Initial atmospheric exposure results



Bare

Corrosion around the SS bolt attached to the aluminum clamp after 2 weeks

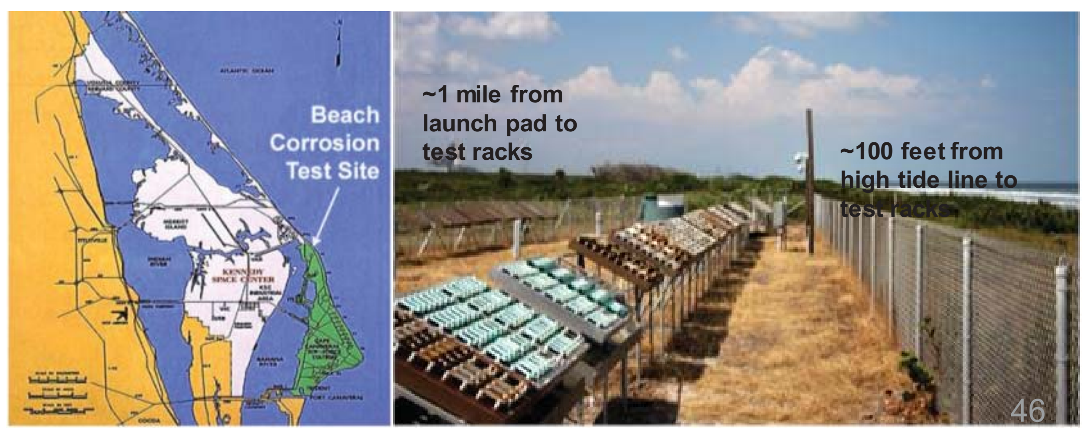
Coated with CPC

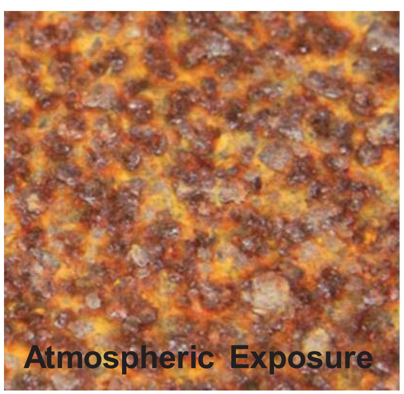
Technology Development

- Long-term prediction of corrosion performance from accelerated tests.
- Coating development (Smart coatings for corrosion detection and control).
- Detection of hidden corrosion.
- Self-healing coatings.

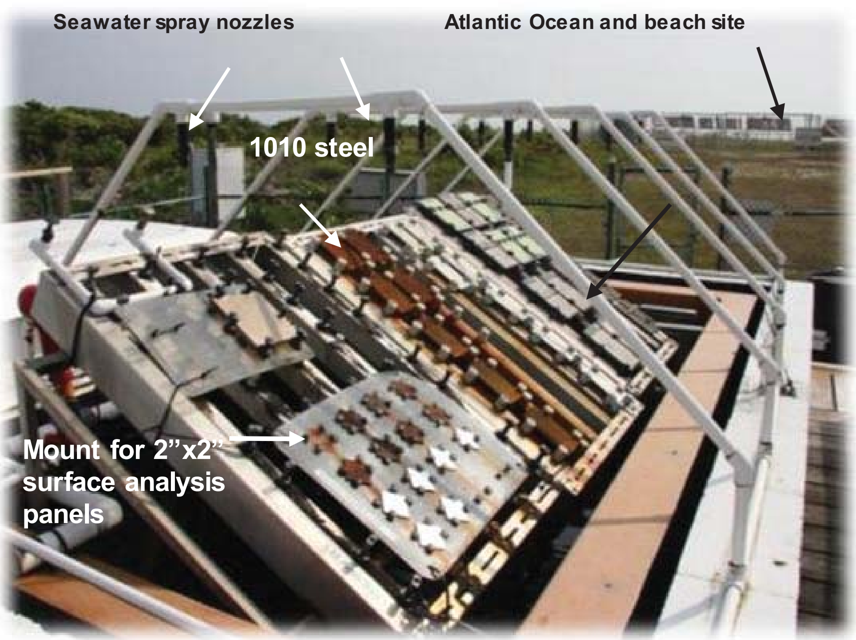
1010 steel (UNS 10100) panels after prolonged exposure

Correlation?





Timescale Correlation between Marine Atmospheric Exposure and Accelerated Corrosion Testing



Alternating Seawater Spray System with exposure panels, and modification for panels used for surface analysis (left). Wet candles exposed to KSC beachside atmospheric conditions and used to measure chloride concentration per month (right).

Summary

- KSC is located in one of the most naturally corrosive areas in North America and has more than 4 decades of experience dealing with corrosion.
- Acidic exhaust from SRBs exacerbate natural corrosive conditions at the launch pads.
- NASA has encountered challenges in corrosion protection since the inception of the Space Program. Some of these challenges have been environmentally driven.
- NASA's Corrosion Technology Laboratory has been actively engaged in anticipating, managing, and preventing corrosion since its foundation in 2000
- NASA is engaged in projects aimed at identifying more environmentally friendly corrosion protection coatings and technologies.
- Current technology development efforts target the development of smart coatings for corrosion detection and control and the development of a new accelerated corrosion test method that correlates with long-term corrosion test methods.
- Website: http://corrosion.ksc.nasa.gov/

NASA's Corrosion Technology Laboratory Team

B.P. Pearman, M.R. Kolody, M.N. Johnsey, J.W. Buhrow, L. Fitzpatrick, J. Zhang, L.M. Calle, T.A. Back, S.T. Jolley, E.L. Montgomery, J.P. Curran, and W. Li