Corrosion Protection for Increased Resiliency of NASA's Launch and Ground Support Equipment

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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, accelerated corrosion testing began (salt fog and electrochemical).
- In 2000, The Corrosion Technology Laboratory was created to achieve KSC's goal of increased participation in research and development.
- In 2000 a computerized corrosion data management system was 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 was approved.
- In 2004, the corrosion technology laboratory started developing smart coatings, based on microencapsulation technology, specifically designed for corrosion control applications (U.S. Patents Nos. 7,790,225, 2010; 8,859, 288, 2014; 9,108,174, 2015 and several pending).

Introduction

- In 2011, NASA-STD-5008B revision updated the standard and added 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.

- In 2014, NASA's Space Technology Roadmap included 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 corrosion protection for increased resiliency of NASA's launch and ground support equipment throughout the history of NASA's Space Program.

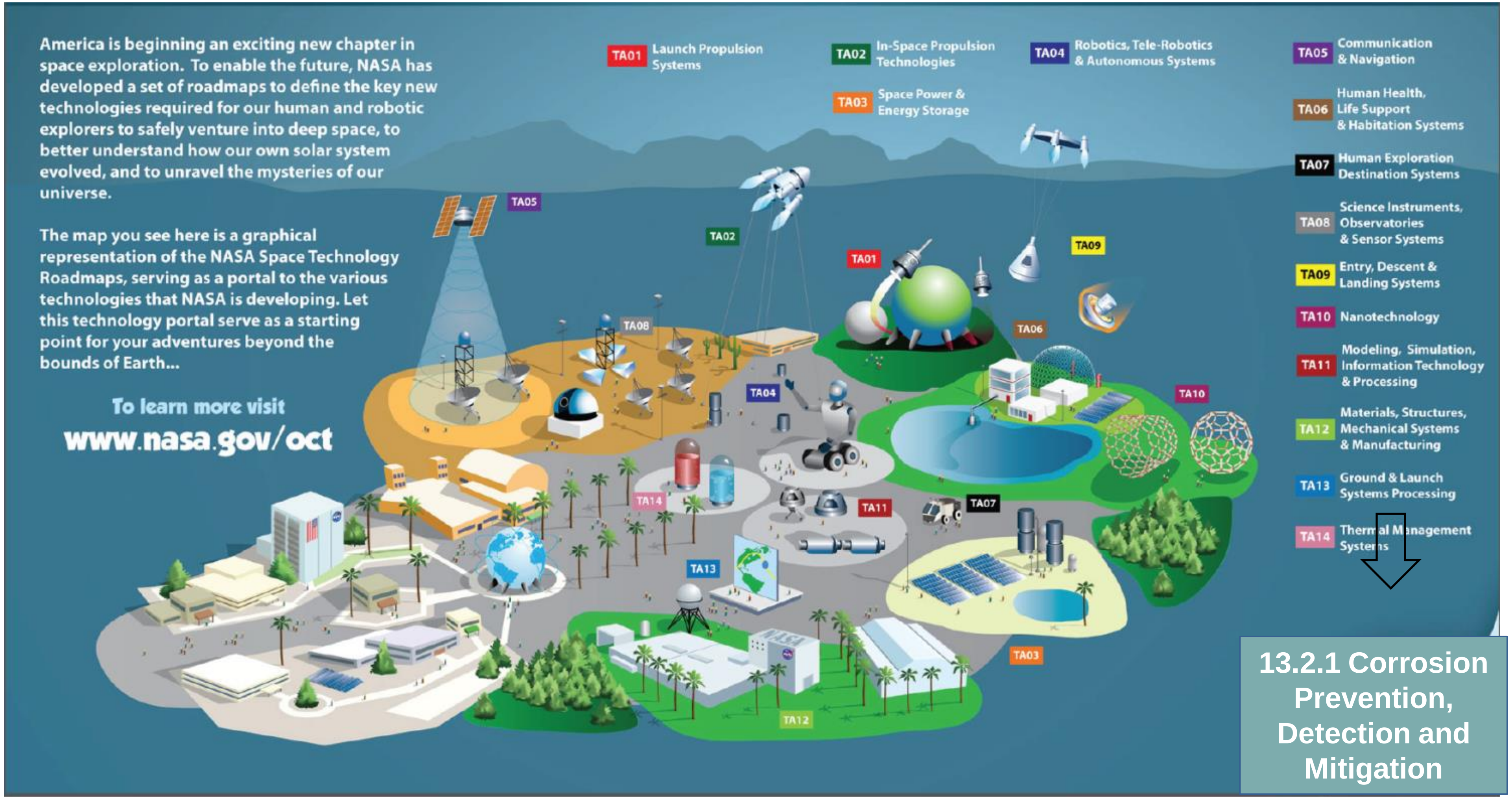
Corrosion Protection for Increased Resiliency of NASA's Launch and Ground Support Equipment Timeline

1962	1966	1981	1985-1987	2000	2004
Space Program starts Corrosion failures begin	Atmospheric exposure testing begins near the launch pads	Space Shuttle introduces acid deposition products that make corrosion worse	Accelerated corrosion testing (salt fog and electrochemical) begins	Corrosion Technology Laboratory is created	The Corrosion Technology Laboratory starts developing new corrosion protection technologies and test methods

Corrosion testing and failure analysis

Corrosion testing and technical innovation

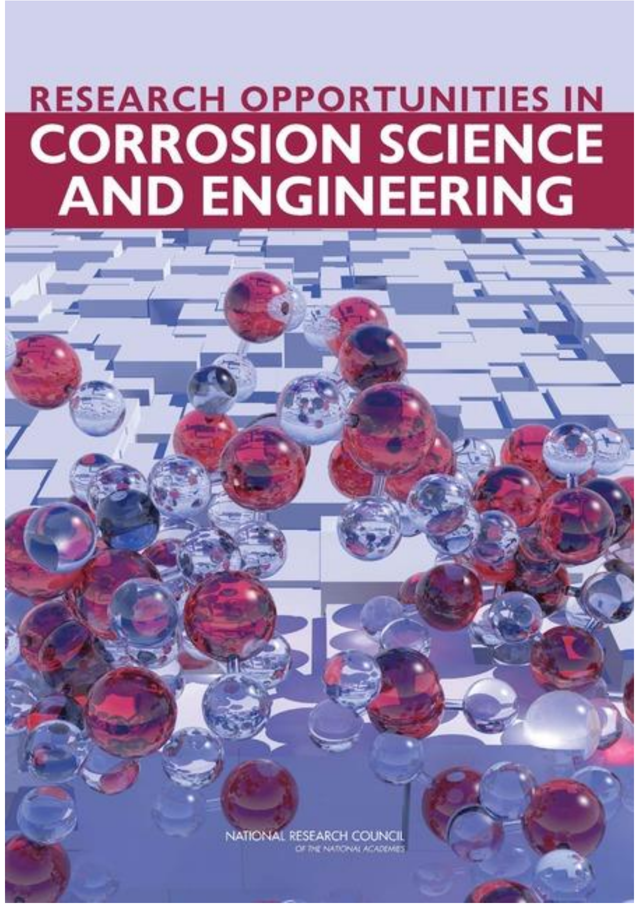
NASA Space Technology Roadmap



13.2.1 Corrosion Prevention, Detection and Mitigation

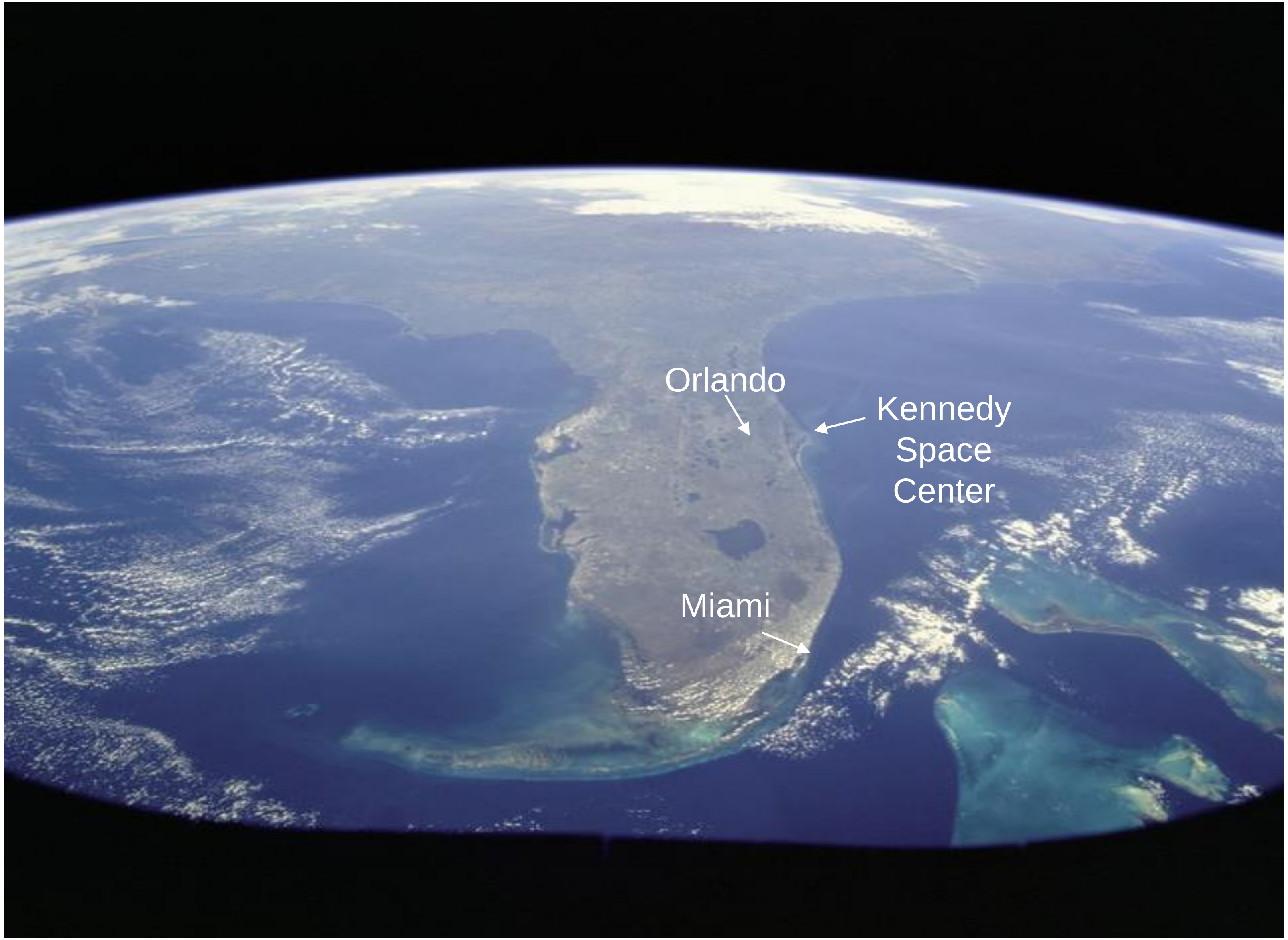
Corrosion Grand Challenges*

- 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)

Where Are We?



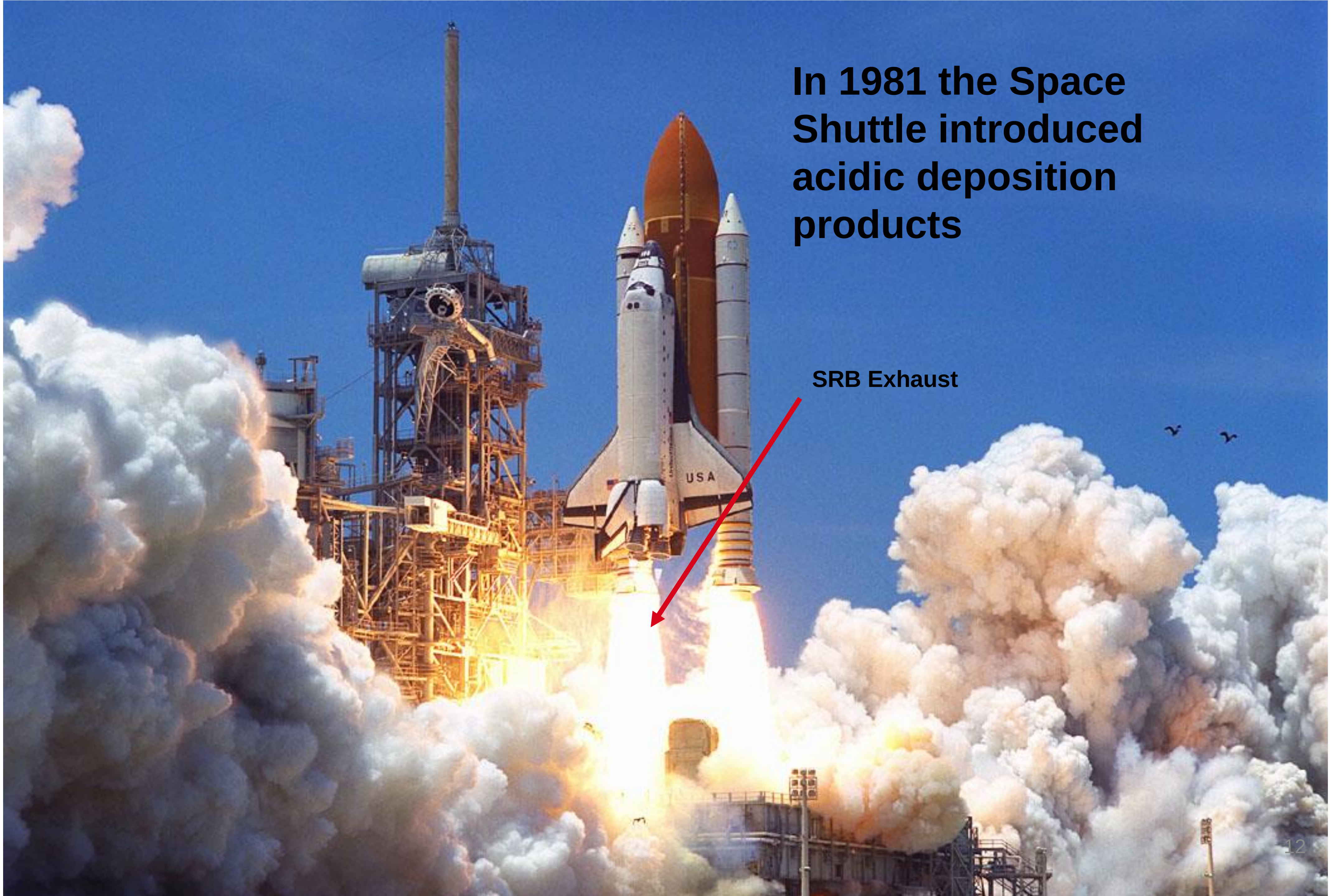
The Kennedy Space Center in Florida, USA, is a special place where we launch rockets from a wild life refuge in one of the most corrosive areas in the world

KSC Natural 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 ^{o}C). Close to 70 tons of hydrochloric acid (HCl) are generated by the combustion products of a rocket’s solid propellant.

In 1981 the Space Shuttle introduced acidic deposition products



Natural Salt Fog Chamber

Corrosion Rates of Carbon Steel

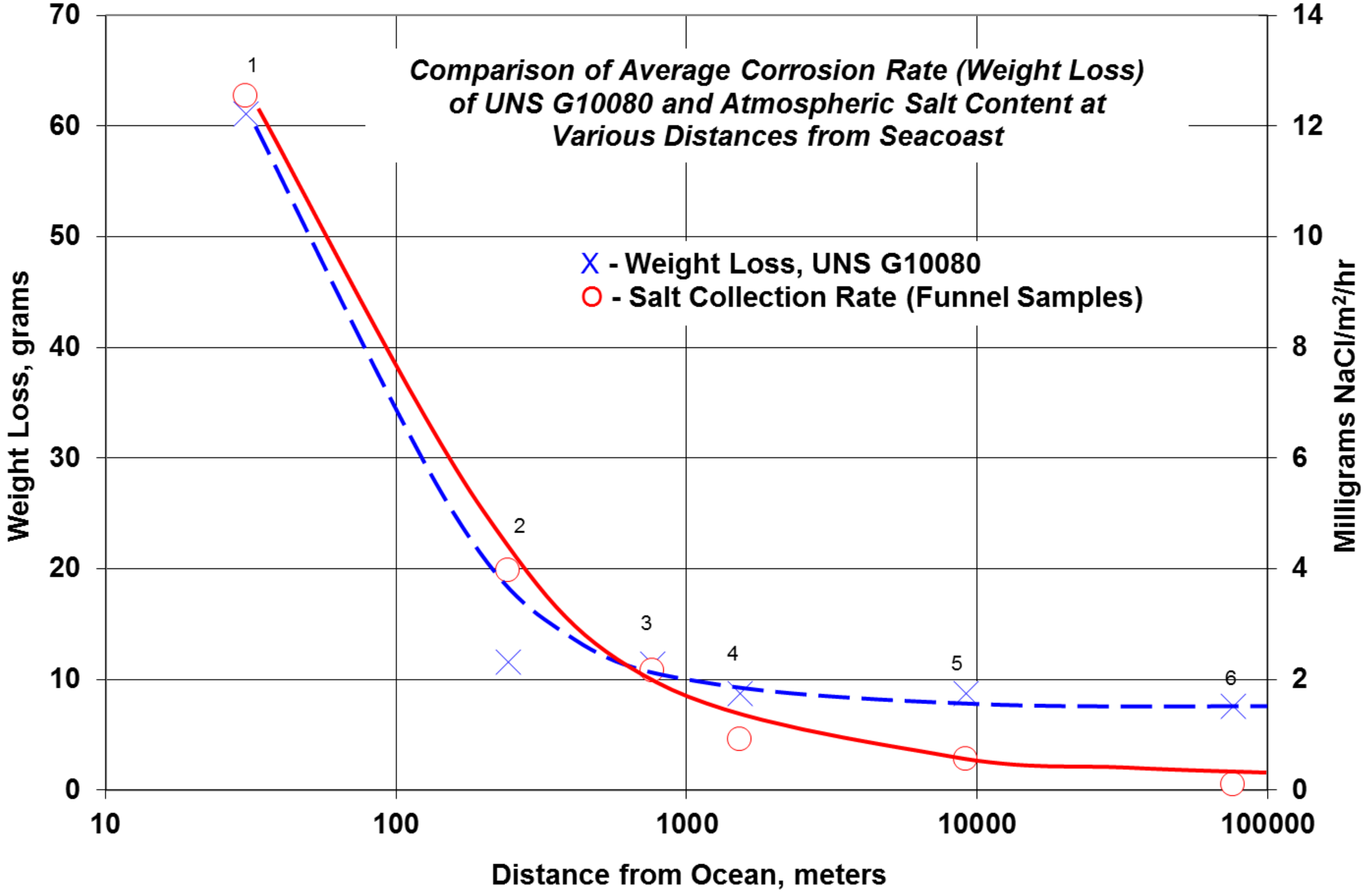
Corrosion rates of carbon steel calibrating specimens at various locations*			
Location	**Type Of Environment**	**Corrosion Rate[a] μm/yr**	**Corrosion Rate[a] mils/yr**
Esquimalt, Vancouver Island, BC, Canada	**Rural marine**	**13**	**0.5**
Pittsburgh, PA	**Industrial**	**30**	**1.2**
Cleveland, OH	**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 = one thousandth of an inch = 0.0254 mm

Changes In Corrosion Rate with Distance from the Ocean



Examples of Launch Pad Corrosion

Enclosed / Inaccessible Areas

Dissimilar Metals

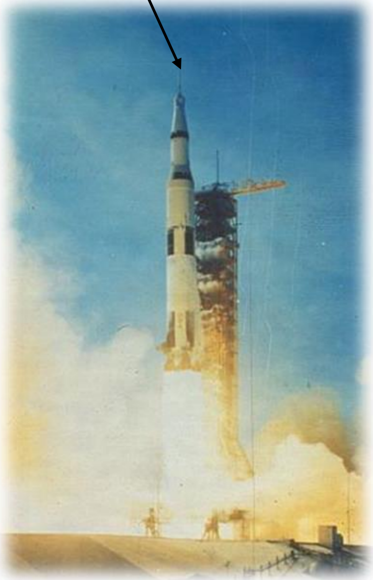
KSC Launch tower structural steel corrosion

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.

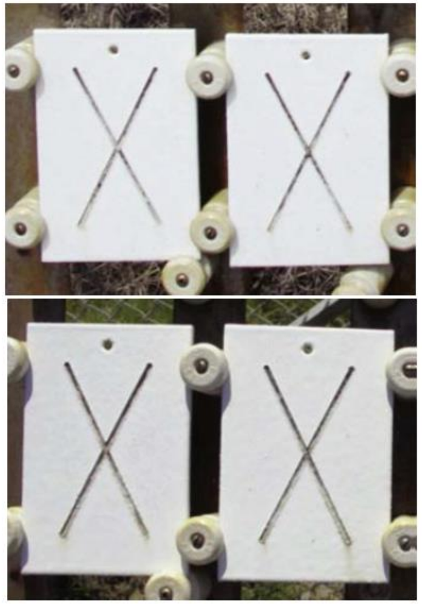
NASA-STD-5008B

- 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

Launch complex 39 zones of exposure

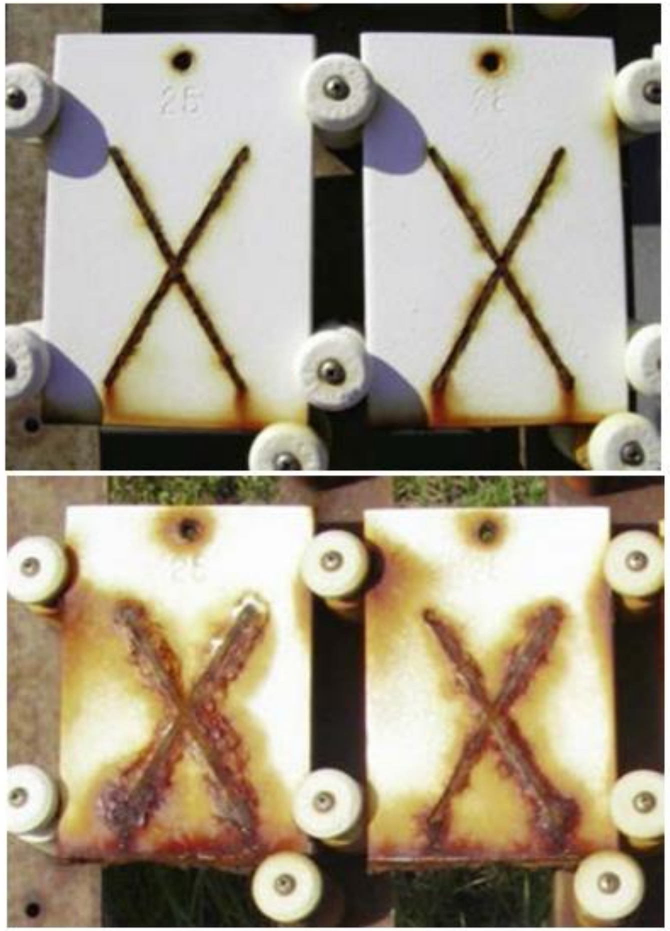
Atmospheric Exposure

Real world exposure at a site that mimics actual performance requirements



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

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.



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

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)

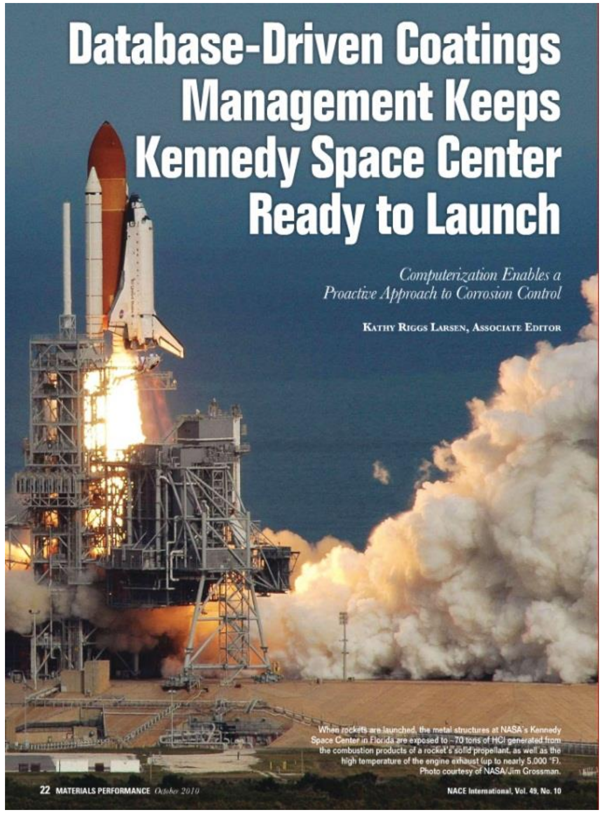
Accelerated testing

Electrochemical testing

Computerized Corrosion Management*

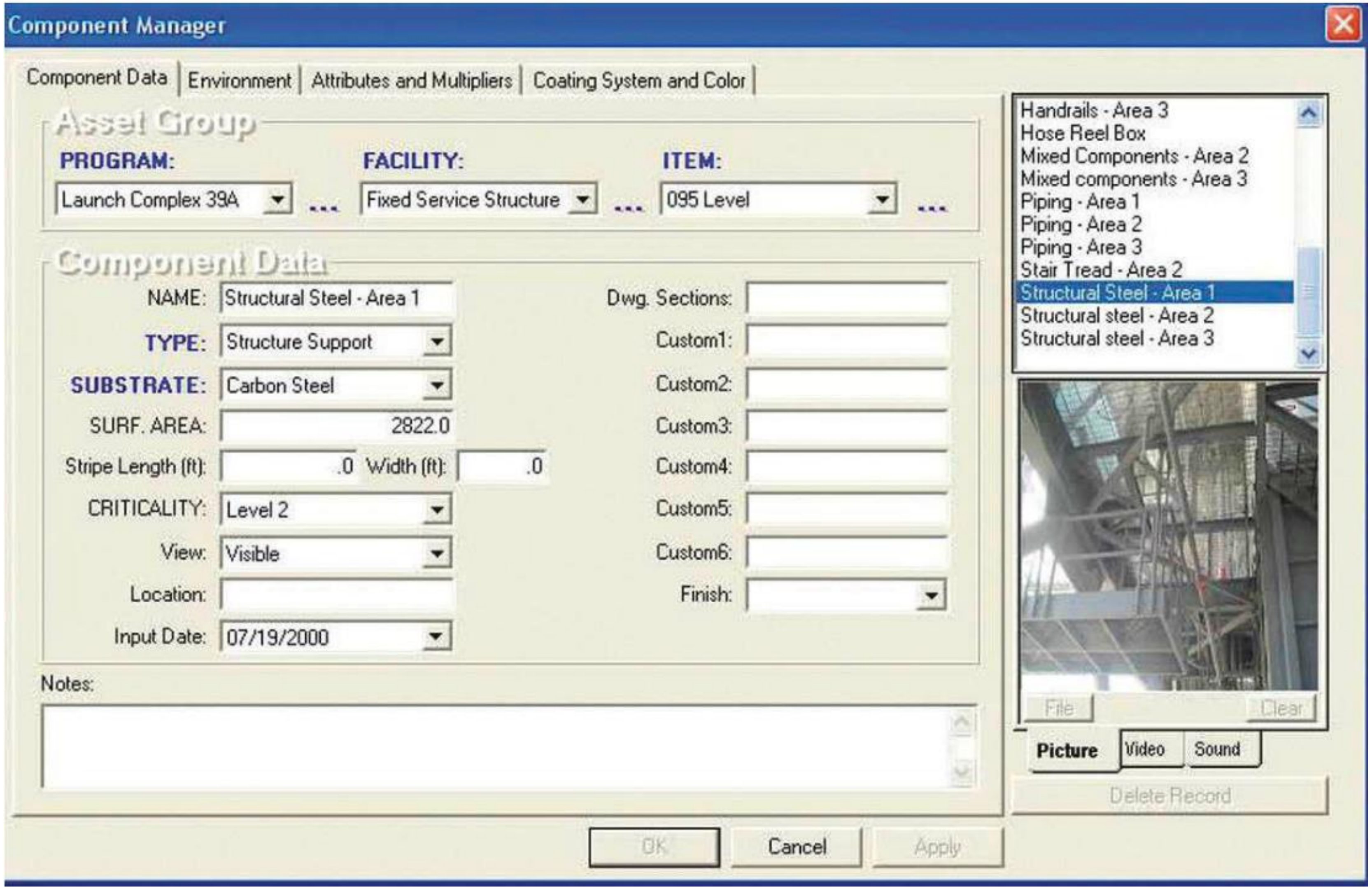
Since 2000, a computerized corrosion management program has been used to keep track of corrosion in more than 3,600 critical components and about 1 million m^2 of surface area.

- 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



October 2010 issue of Materials Performance (MP)

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

Environmentally Driven Projects

NASA has been facing environmentally driven challenges in corrosion control since the inception of the Space Program.
Many projects thruought the years have been aimed at finding alternate coatings to replace high VOC and hexavalent chromium coatings for lunch pad structures and ground support equipment.

Current environmentally driven projects include:

- Alternative to Nitric Acid Passivation
- Hexavalent Chrome alternative Coatings Systems
- Environmentally Friendly Corrosion Protective Compounds (CPCs)
- Smart and Multifunctional Corrosion Protective Coating Development
- Improved Accelerated Corrosion Testing 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

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 .

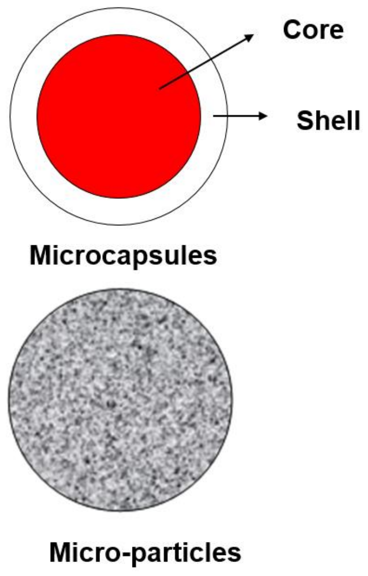
Dead tree/fish label warnings required in Europe for zinc primers

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

Keep out of waterways. (US MSDS)

Smart Coatings for Corrosion Control

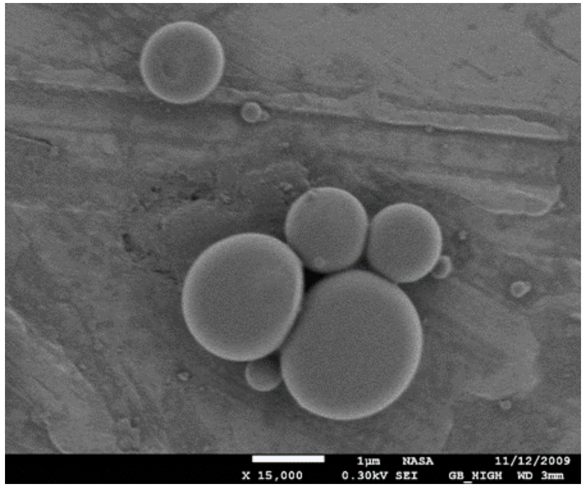
- The use of "smart coatings" for corrosion sensing and control relies on the changes that occur when a material degrades as a result of its interaction with a corrosive environment.
- Such transformations can be used for detecting and repairing corrosion damage.
- The Corrosion Technology Laboratory 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.



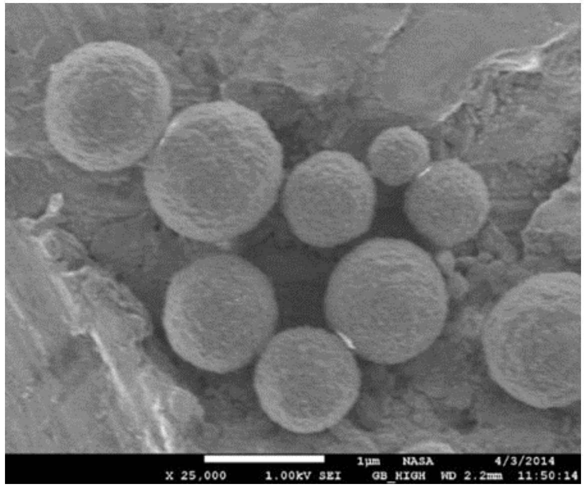
Feedback-Active Micro-containers for Corrosion Detection and Control

- Containers with an active ingredient-rich core and stimuli-responsive shell (microcapsules)

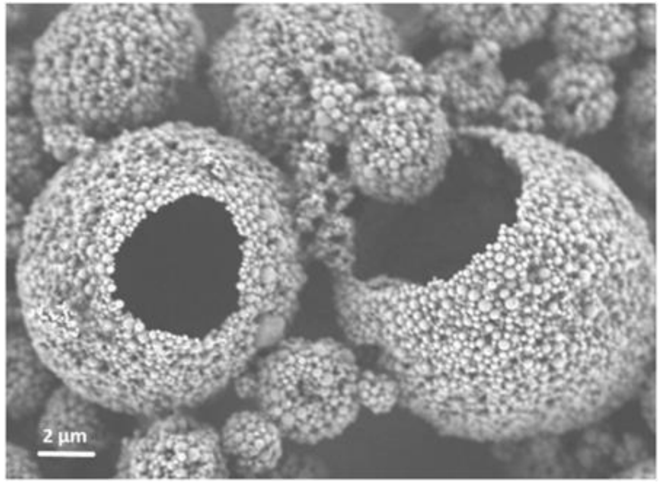
- Containers with an active ingredient incorporated into a stimuli-responsive matrix (micro-particles). Matrix can be organic (pH sensitive polymer) or inorganic (porous silica)



pH-sensitive microcapsules

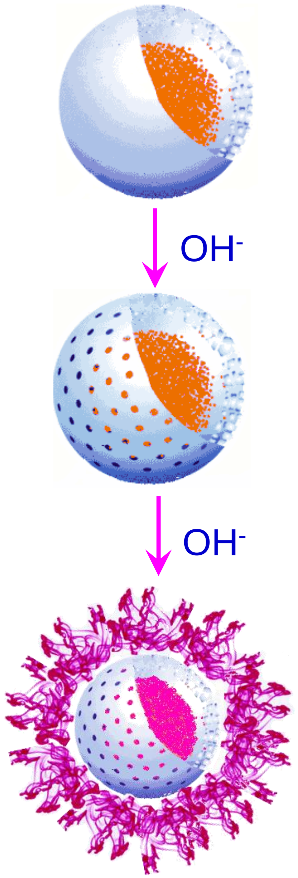


pH-sensitive micro-particles



Inorganic micro-containers

pH-triggered Release Microcapsules

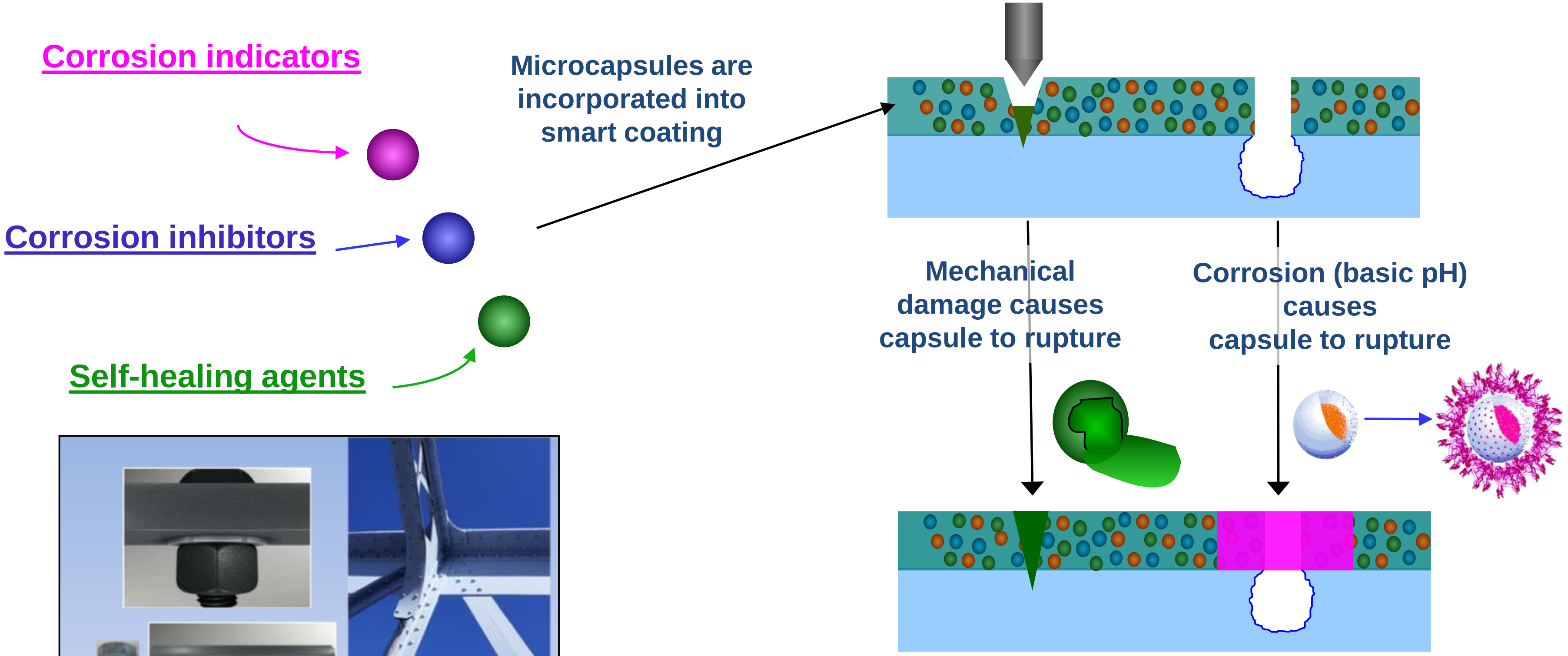


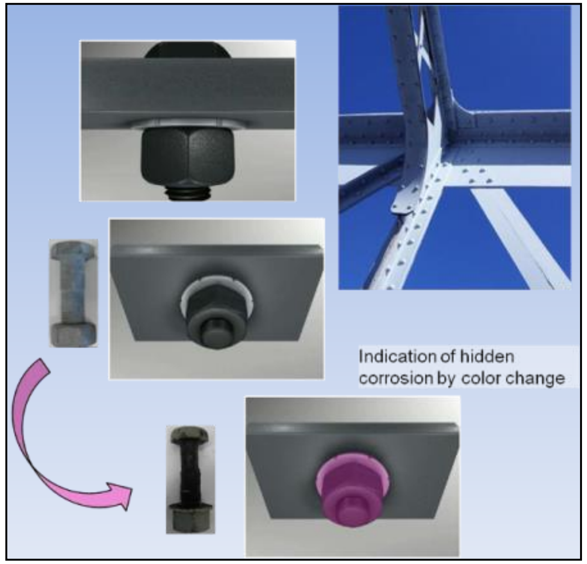
Microcapsule containing pH indicator (inhibitor, self healing agents)

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



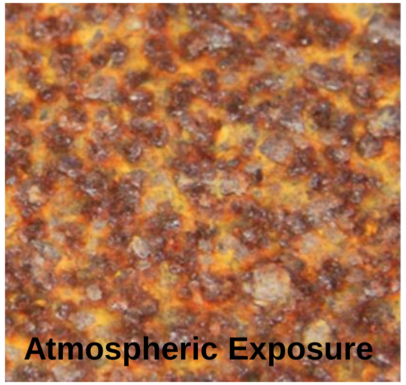


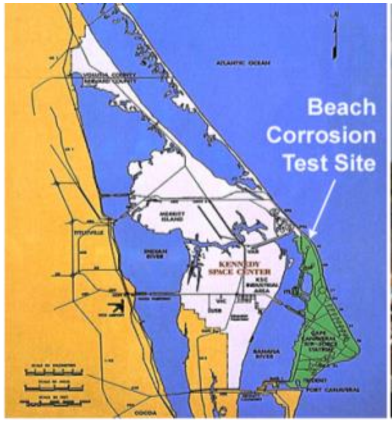
Improved Accelerated Corrosion Testing

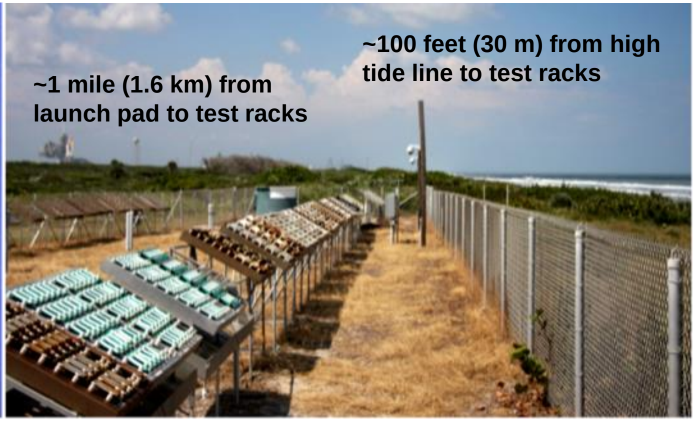
- Long-term prediction of corrosion performance from accelerated tests.

1010 steel (UNS 10100) panels after prolonged exposure

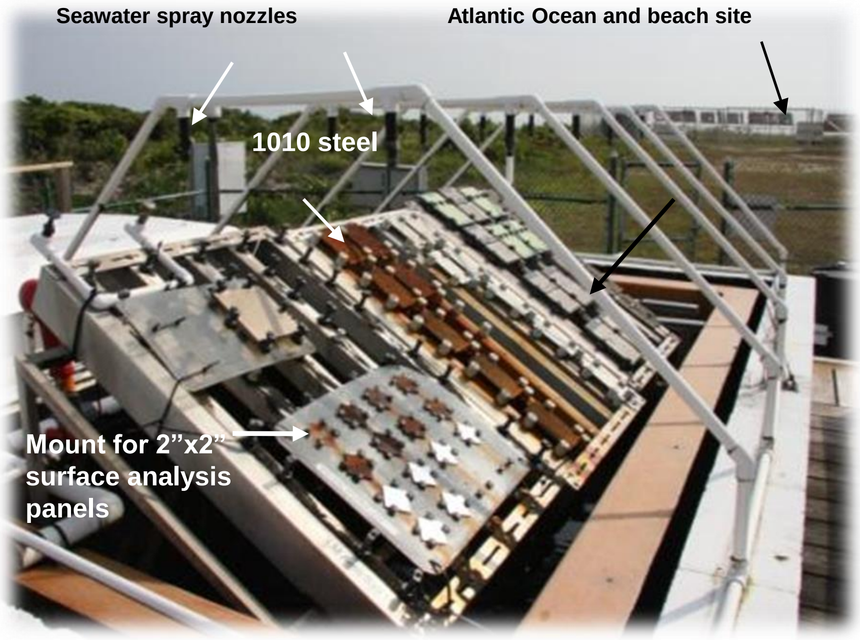
Correlation?







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

- NASA has been dealing with corrosion problems since the inception of the Space Program.
- Acidic exhaust from SRBs exacerbate natural corrosive conditions at the launch pads.
- NASA's Corrosion Technology Laboratory has been actively engaged in anticipating, managing, and preventing corrosion of launch and ground support equipment.
- 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, the development of a new accelerated corrosion test method that correlates with long-term corrosion test methods, and the development of an environmentally friendly metal passivation method.
- Website: http://corrosion.ksc.nasa.gov/

NASA's Corrosion Technology Laboratory Team

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