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Technology Evaluation for Environmental Risk Mitigation Compendium

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September 2017

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Executive Summary

Introduction

Since 1998, the Technology Evaluation for Environmental Risk Mitigation (TEERM) Principal Center and its predecessor organization, the Acquisition Pollution Prevention (AP2) Program Office, have supported the National Aeronautics and Space Administration (NASA) in identifying technology solutions to technical and cost risks to NASA programs and mission driven by environmental regulations and requirement constraints. The Prime Contractor, ITB, Inc. manages TEERM for the NASA Environmental Management Division (EMD).

For 18 years, TEERM researched the commercial and government marketplace to locate viable, available, and environmentally preferable technologies that met NASA's array of needs. TEERM focused on addressing environmentally-driven risks of direct concern to NASA programs and facilities, including Hazardous Materials (HazMat) in NASA operations and the replacement of materials that became obsolete because of environmental regulations. TEERM and EMD emphasized partnering with organizations inside and outside of NASA to share in costs and benefits of the technology testing and validation projects TEERM managed.

The Space Shuttle Program (SSP) was an active partner with TEERM in evaluating new technologies to mitigate these risks. After the retirement of the Space Shuttle, funding from NASA partners to address environmentally-driven risks became increasingly difficult to find. The paradigm for the new set of launch vehicles development is not as mature as existed for the Shuttle. Because of the new focus on commercial space transportation, there are fewer advantages for commercial partners to collaborate on technology solutions in a less cooperative and more competitive working environment. Environmentally-driven risks will still impact NASA, but the risk has shifted to commercial partners.

In 2017, the NASA EMD made the decision to terminate the TEERM Principal Center. As of this report, TEERM has entered its 18th year of providing technology identification and evaluation services for NASA and its partners. Our work has provided NASA and our partners with technical research expertise dedicated to meeting the complex needs of NASA programs and centers. This Compendium Report documents TEERM and AP2 project successes and lessons learned to ensure that this material will continue to be readily available to NASA and other interested parties.

Environmentally-Driven Risks to NASA Mission

Domestic and international environmental regulations and requirements have increased dramatically since the creation of the United States (U.S.) Environmental Protection Agency (EPA) in 1970. These environmental requirements create risks for Federal Agencies like NASA. Environmentally-driven risks to the NASA mission include human health and environmental risks, materials obsolescence risks, and cost and sustainability risks. AP2 and TEERM sought to identify and mitigate some of these risks for NASA.

History

The Joint Group on Pollution Prevention (JG-PP) was chartered by the U.S. Department of Defense (DoD) and NASA Headquarters (HQ) to establish a standardized process for government and industry to work together to validate and implement cleaner and less expensive processes at military and industrial facilities. JG-PP represented a partnership among the military services, NASA, and the Defense Logistics Agency (DLA).

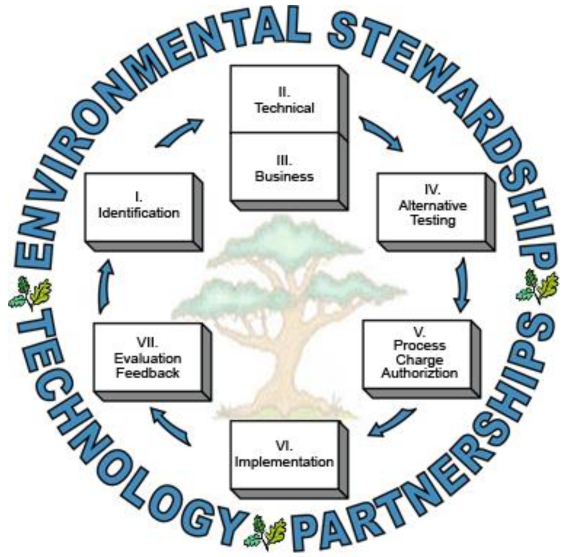
In 1998, NASA established the NASA AP2 Program Office to serve as the Agency's primary liaison with JG-PP. The mission of the AP2 Program Office was to reduce duplication among the Agency, DoD services, and international partners. AP2 was tasked to identify and integrate Pollution Prevention (P2) needs, systems safety, health risk assessments, and environmental impact assessments into the entire life cycle of NASA programs and processes – from concept development to final disposal. This integration was accomplished through joint activities across three business entities involving (1) NASA centers and programs; (2) NASA-DoD weapon systems acquisition, operation, and sustainment process owners; and (3) NASA-international government activities supporting manufacturing and maintenance processes.

In 2007, NASA created TEERM as a refocusing of the AP2 Program Office. Numerous organizations played a role in TEERM development, including JG-PP, Shuttle Environmental Assurance (SEA) Initiative, and the Centre for Pollution Prevention Program (C3P).

Environmentally-driven risks and resulting impacts to the NASA mission changed over time along with the changes and increases in environmental requirements. The initial AP2 focus was P2. SSP concerns related to the phase-out of critical Ozone Depleting Substances (ODSs) helped shift the AP2 (now TEERM) focus to mission risks including materials obsolescence. After the Space Shuttle retirement, TEERM then shifted emphasis to include energy efficiency and facility resiliency projects to reduce cost and risk for NASA. Additionally, TEERM continued various materials replacement projects of importance to NASA.

TEERM Processes

TEERM projects and integration activities were designed to evaluate, in an unbiased fashion, technological solutions to environmentally-driven risks impacting NASA. The TEERM approach to projects was based on the approach developed by JG-PP and included an initial opportunity assessment to identify environmentally-driven risk, a project formulation phase that included planning and partner commitments, and an execution phase. Project formulation was central to TEERM's approach and success. Defining the problem and being able to communicate how this problem relates to the various stakeholders/partners proved critical in acquiring contributions in either direct or in-kind support.



TEERM worked with project partners with similar needs to develop and execute test plans for new, more environmentally-friendly materials and processes. The TEERM approach included outreach and dissemination of Government-approved project testing data and reports. This document references reports publicly available through the NASA Technical Support Server (NTRS) (https://www.sti.nasa.gov/) or other public resources.

Beginning in 2003, AP2 (and TEERM) collaborated with European partners to hold a workshop for technical interchange and to help identify new project opportunities. Co-sponsors have included C3P and the European Space Agency (ESA).

TEERM and AP2 Projects

Major TEERM and AP2 projects included projects with an environmental focus (e.g., waste minimization, recycling, corrosion prevention, material obsolescence and remediation) and those focused on energy and sustainable development.

Waste Minimization and Hazardous Waste Treatment

- AP2 conducted Pollution Prevention Opportunity Needs Assessments (PPONAs) at NASA centers, Air Force locations, and in Portugal in collaboration with C3P.
- TEERM developed and managed a project sponsored by NASA Kennedy Space Center (KSC) Ground Systems Development and Operations Program (GSDOP) Office to evaluate bio-based citric acid as an alternative for nitric acid passivation.

Recycling and Biodegradable Material

- TEERM initiated the first-ever demonstration at a NASA site for recycling Spent Blast Media (SBM) for use in onsite concrete construction projects. As a result, this recycle/reuse technology is approved by NASA KSC for use in future contract language.
- TEERM leveraged knowledge from a National Defense Center for Energy and Environment (NDCEE) Corn Hybrid Polymer (CHP) blasting project to initiate a NASA Johnson Space Center (JSC) study on the technology. TEERM arranged for a technology demonstration and worked with JSC on defining technical requirements and identifying potential technology transition obstacles.

Hazardous Air Pollutants (HAPs) Treatment

- A novel membrane technology capable of removing Volatile Organic Compounds (VOCs) from nearly any entrained air stream was tested at two NASA centers. The project found dramatic reduction of VOCs to the atmosphere (>90%) and a cost savings over thermal oxidation and conventional membrane technologies.

Corrosion Prevention and Control

- TEERM identified and disseminated data on replacements for coatings containing Hexavalent Chromium (CrVI). TEERM managed collaborative studies with direct and in-kind contributions from outside NASA EMD, including U.S. Navy Air Systems Command (NAVAIR), ESA, and GSDOP. From 2003 to 2014, TEERM efforts resulted in almost $2M being awarded to the NASA Corrosion Technology Laboratory (CTL).
- TEERM initiated and managed a project to conduct flight-testing of several CrVI-free coatings aboard a NASA P-3 aircraft at NASA Wallops Flight Facility (WFF). This alternative coating demonstration/validation on a NASA aircraft represents the first field demonstration on aircraft flight equipment for the Agency. Primary among the innovative features of some of the coatings is their corrosion inhibiting makeup.
- The Isocyanate-Free Coatings for Structural Steel project resulted in five systems being added to the Approved Products List (APL) of NASA-Standard (STD)-5008. These coating systems were the first low-VOC coatings added to the APL, supplying maintenance personnel environmentally-friendly alternatives while ensuring that performance standards are met.
- TEERM worked with NASA GSDOP, KSC CTL, WFF, White Sands Test Facility (WSTF), and Air Force Space Command (AFSPC) to identify, demonstrate, and validate environmentally-preferable coatings. Four coating systems passed the minimum criteria set forth in KSC NASA-STD-5008B.
- TEERM managed a large, multi-Agency collaborative effort to demonstrate/validate alternative coatings to reduce heavy metals, most notably CrVI.
- TEERM initiated an alternative coatings demonstration/validation project with ESA. One innovative aspect of this project was TEERM's identification of coatings uniquely available in Europe that offer promise for NASA and DoD applications.

ODS, Solvent Substitution, and Aqueous Cleaners

- The AP2 Program Office developed a "Consumer's Guide to Alternative Parts Washers" to assist environmental managers, shop owners, and procurement personnel in deciding which environmentally-preferable parts washer will work best for their shops.
- TEERM leveraged the results of an Environmental Security Technology Certification Program (ESTCP) on a Portable Laser Coating Removal System (PLCRS) to start an intensive series of field demonstrations at Glenn Research Center (GRC), Wright-Patterson Air Force Base (WPAFB), and KSC. Lasers were tested on a variety of Ground Support Equipment (GSE) from several NASA centers and Boeing for use on various types of Orbiter hardware including tile cavity applications as well as aluminum honeycomb, Inconel, and other sensitive substrates.

Lead in Electronics

- AP2 performed a comprehensive baseline study of the risks associated with continued use of eutectic tin-lead solder alloys for electronic soldering and a state of the technology assessment of lead-free alloys.
- TEERM garnered project buy-in from various military and aerospace partners to test and evaluate the reliability of promising lead-free solder alloys. TEERM authored the project's industry-leading joint test plan, which is internationally recognized.

Green Engineering and Energy Solutions

- TEERM initiated an assessment of wind turbine performance at JSC with Subject Matter Experts (SMEs) from the U.S. Department of Energy (DOE) National Renewable Energy Laboratory (NREL).
- TEERM supported a 12-month field demonstration of an innovative hydrogen fuel cell mobile light tower coupled with advanced energy-efficient lighting at KSC. This technology demonstration provided an important step to DOE in bringing hydrogen fuel cell technology to civilian and government/military support equipment.
- In collaboration with JSC, DOE, NREL, and two universities, TEERM formulated a project to validate a model to predict the ability of green roofs to store water.

Benefits and Recommendations

TEERM activities benefitted NASA by identifying and cost-effectively evaluating mitigation technologies that saved millions of dollars without impacting NASA's mission capability or readiness. TEERM supported the transition of new technologies to NASA centers and programs, and through technology verification studies, avoided the costly implementation of unproven solutions. Due to its extensive network of contacts, TEERM became an excellent resource for finding existing solutions to problems. If no solution was readily known, TEERM worked to identify potential solutions and partners for validation efforts. Over its 18 years, TEERM evaluated 243 "green" solutions for NASA, of which 67 were recommended for insertion.

In summary, TEERM:

- was user driven;
- provided performance-based results;
- avoided duplicating technology efforts;
- linked its activities to NASA's mission;
- communicated its findings across NASA, other federal agencies, and industry; and
- supported the transition of validated technologies to NASA centers and programs.

Recommendations based on the successful TEERM approach implementation include:

- apply collaborative, risk-based approach to other disciplines (e.g., facility resilience), and
- maintain relationships with outside agencies and industry.

1 Introduction

Beginning in 1998, the Technology Evaluation for Environmental Risk Mitigation (TEERM) Principal Center and its predecessor organization [Acquisition Pollution Prevention (AP2) Program] supported the National Aeronautics and Space Administration (NASA) in identifying technology solutions to risks and costs to NASA programs driven by environmental regulations and requirements. The NASA Environmental Management Division (EMD) awarded the first Basic Ordering Agreement to manage AP2 to ITB, Inc, of Dayton, Ohio in March 1999. ITB has served as the Prime Contractor since that date.

TEERM researched the commercial and government marketplace to locate viable and available technologies that met NASA's array of needs. TEERM focused on addressing environmentally-driven risks of direct concern to NASA programs and facilities, including Hazardous Materials (HazMats) in NASA operations and materials that became obsolescent because of environmental regulations. TEERM and EMD emphasized partnering with organizations inside and outside of NASA to share in the costs and benefits of the technology testing and validation projects TEERM managed.

The Space Shuttle Program (SSP) and its contractors was an active partner with TEERM in evaluating new technologies to mitigate these risks. After the Space Shuttle retirement, funding from NASA partners to address environmentally-driven risks became increasingly difficult to obtain. The paradigm for the new set of launch vehicles development is not mature as it was for the Shuttle. Because of the new focus on commercial space transportation, there are fewer advantages for commercial partners to collaborate on technology solutions in a less cooperative and more competitive working environment. Environmentally-driven risks will still impact NASA, but the risk has shifted to commercial partners.

In 2017, NASA EMD made the decision to terminate the TEERM Principal Center. This Compendium Report documents TEERM and AP2 project successes and lessons learned to ensure that this material will continue to be readily available to NASA and other interested parties. The Compendium Report traces the evolution of TEERM based on evolving risks and requirements for NASA and its relationship to the SSP, the U.S. Department of Defense (DoD), the European Space Agency (ESA), and other public and private stakeholders.

This Compendium Report also documents project details from Project Summaries and Joint Test Plans and describes project stakeholders and collaborative effort results. TEERM evolved directly from AP2; was funded by the same NASA organization (EMD); managed by the same contractor (ITB); and inherited its approach, partners, and ongoing projects. Additionally, this report documents AP2 projects and successes. Documents published by TEERM are available on the NASA Scientific and Technical Program website (https://www.sti.nasa.gov/).

The text discusses only major projects or those endeavors that contributed to major projects; however, Appendix B lists all projects in which TEERM played a substantial role.

2 Technology Evaluation for Environmental Risk Mitigation Requirements

2.1 Drivers and Risks

Beginning in the 1970s, many environmental, health, and safety laws and associated regulations were enacted in the U.S. Early regulations focused on controlling environmental emissions to air and water, reducing occupational exposures, and managing hazardous waste. Later regulations began to restrict the use of Ozone Depleting Substances (ODSs) and hazardous chemicals in commerce in the U.S. and Europe. Laws, regulations, and Executive Orders (EOs) that required an increase in energy efficiency and emphasis on sustainability followed.

These environmental requirements create risks for Federal Agencies like NASA. Risk is characterized by the combination of the likelihood of occurrence of an undesired event and the severity of the undesired event. Potential impacts associated with an increase in environmental requirements include:

- ***Human Health and Environmental Risks*** – NASA operations use HazMats as well as create waste and emissions that can be hazardous to human health and the environment. There is a risk of occupational exposure and releases to the environment. Potential impacts include human health effects, environmental impacts, non-compliance with regulations, and increased cost and liability.
- ***Materials Obsolescence Risks*** – Risks to the NASA mission include potential loss of qualified materials resulting in the reduced performance of available replacements and the associated costs and schedule impacts.
- ***Cost and Sustainability Risks*** – Risks to the NASA mission include costs and liability associated with climate change, Greenhouse Gas (GHG) emissions, energy consumption, and hazardous and solid waste generation.

Table 1 lists some specific environmental regulations and requirements that create risks to the NASA mission. Initial risks were driven by the Clean Air Act (CAA); Clean Water Act (CWA); Resource Conservation and Recovery Act (RCRA); and Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). These risks were related to the management of emissions and hazardous waste and created a business case for Pollution Prevention (P2) as a way to proactively reduce risks and costs.

The Montreal Protocol requirement to phase-out ODSs created immediate obsolescence risks to NASA, especially to the SSP, which relied on ODSs for very specific cleaning and foam applications. The European Union (EU) Waste Electrical and Electronic Equipment (WEEE) and Restriction on Hazardous Substances (RoHS) regulations resulted in risks associated with the potential entry of lead-free electronics into systems that required lead. The EU Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulations, in combination with increasing concerns about Hexavalent Chromium (CrVI), Volatile Organic Compounds (VOCs), and other chemicals in the U.S. put additional pressure on manufacturers to reduce the use of HazMats, thus creating more obsolescence risks for NASA.

Table 1. *Overview of environmentally-driven requirements / impacts to NASA mission***.**

Law/Regulation/EO	Impact
Environment and Occupational Health	
National Oil and Hazardous Substances Pollution Contingency Plan (NCP), 1968	Established national response capability for responding to oil spills and hazardous substance releases. In 1980, the NCP was broadened to cover releases at hazardous waste sites requiring emergency removal actions. https://www.epa.gov/emergency-response/national-oil-and-hazardous-substances-pollution-contingency-plan-ncp-overview
CAA 1970	The CAA authorized development of federal and state regulations to limit emissions from stationary and mobile sources. Programs initiated include: National Ambient Air Quality Standards (NAAQS), New Source Performance Standards (NSPS), and National Emission Standards for Hazardous Air Pollutants (NESHAP). The regulations promulgated in support of the CAA created the need to reduce releases to the air, resulting in cost impacts. https://www.epa.gov/laws-regulations/summary-clean-air-act
Occupational Safety and Health Act 1970	Created the Occupational Safety and Health Administration (OSHA) and Permissible Exposure Limits (PELs) development. PELs reductions can increase engineering controls and personal protective equipment required. Can result in additional operating costs. Vendors may be reluctant to use highly regulated materials (e.g., cadmium and chromium). https://www.osha.gov/pls/oshaweb/owasrch.search_form?p_doc_type=OSHACT
CWA 1972	CWA Effluent Guidelines restrict allowable wastewater concentrations and can indirectly affect materials usage. https://www.epa.gov/laws-regulations/summary-clean-water-act
RCRA 1976	RCRA created hazardous waste definitions and requirements. RCRA also indirectly affected materials, leading to cases where vendors found requirements too costly to implement and were forced to cease manufacture. https://www.epa.gov/rcra
Toxic Substances Control Act (TSCA) 1976	TSCA Significant New Use Rules (SNURs) created limitations on domestic materials manufacture and importation. Can affect cost and availability of materials. https://www.epa.gov/laws-regulations/summary-toxic-substances-control-act
CERCLA 1980	Historical operations at NASA sites have resulted in soil and groundwater contamination, for which NASA is responsible to remediate under CERCLA and RCRA. This remediation is a large cost liability for NASA. https://www.epa.gov/superfund/superfund-cercla-overview
Montreal Protocol 1989 **CAA Amendments of 1990 Title VI**	The Montreal Protocol is an international agreement that phases out the production and consumption of ODSs. In the U.S., this agreement is codified into law in Title VI of the CAA Amendments of 1990 and has been implemented in various regulations. Phased out critical materials used in precision cleaning and foam blowing include Class I ODSs: Chlorofluorocarbons (CFCs), Freon, Halon, Trichloroethane (TCA); and Class II ODSs: Hydrochlorofluorocarbon 141b (HCFC 141b). http://ozone.unep.org/en/treaties-and-decisions/montreal-protocol-substances-deplete-ozone-layer, https://www.epa.gov/clean-air-act-overview/1990-clean-air-act-amendment-summary-title-vi
CAA Amendments of 1990 Title V	Title V established an operating permit requirement for large sources, making compliance assessment much easier. Title V rolls all existing requirements into one place'. https://www.epa.gov/clean-air-act-overview/1990-clean-air-act-amendment-summary-title-v
CAA Amendments of 1990 Sec 183 (e)	CAA amendments of 1990 establish National Volatile Organic Compound (VOC) regulations and Control Techniques Guidelines (CTGs). These requirements for VOC regulations restrict use of volatile organic materials in certain areas. Forced reformulation of coatings NASA relied on using. https://www.epa.gov/stationary-sources-air-pollution/clean-air-act-guidelines-and-standards-

Law/Regulation/EO	Impact
CAA Amendments of 1990 Title III	Updated CAA Amendments of 1970 section 112. NESHAP: Industry-specific regulations that restrict usage of materials in specific applications. Two-tiered system of regulation; an initial technology-based approach followed by a secondary harm-based standard designed to control residual risks. https://www.epa.gov/clean-air-act-overview/1990-clean-air-act-amendment-summary-title-iii
European Union (EU) WEEE 2002 (Amended 2006, 2009, 2012)	WEEE set collection, recycling, and recovery targets for electrical goods and was part of an initiative to minimize disposal of hazardous constituents from electrical waste. Restrictions could influence U.S. manufacturers to stop production or to make changes in product formulations. http://ec.europa.eu/environment/waste/weee/index_en.htm.
EU RoHS 2002	RoHS banned certain new and existing electronic products containing more than the designated maximum allowable levels of lead, cadmium, CrVI, mercury, polybrominated biphenyls, and polybrominated diphenyl ethers. Restrictions could influence U.S. manufacturers to stop production or to make changes in product formulations and drove the move to lead-free electronics. http://ec.europa.eu/environment/waste/rohs_eee/index_en.htm
EU REACH 2006	Requires the registration of approximately 30,000 chemical substances in use. May result in limitations or bans on sale and use of certain substances. Restrictions could influence U.S. manufacturers to stop production or to make changes in product formulations. https://echa.europa.eu/regulations/reach/legislation
Energy and Sustainability	
Energy Policy Act of 2005	The Energy Policy Act https://www.congress.gov/bill/109th-congress/house-bill/6 required that—to the extent economically feasible and technically practicable—the following amounts of the total electricity used by the Federal Government come from renewable energy: 3% for 2007 to 2009, 5%, for 2010 to 2012, and 7.5% from 2013.
EO 13423, Strengthening Federal Environmental, Energy, and Transportation Management 2007	EO13423 https://www.fedcenter.gov/programs/eo13423/ required agencies to reduce GHGs through a reduction in energy intensity of 3% a year or 30% by the end of Fiscal Year (FY) 2015. Federal agencies must ensure that at least half of renewable energy comes from new renewable sources and agencies must reduce water consumption by 2% annually through FY2015.
Energy Independence and Security Act (EISA) of 2007	EISA 2007 https://www.congress.gov/bill/110th-congress/house-bill/6 increased the Federal energy reduction goal from 2% per year to 3% per year, resulting in 30% greater efficiency by 2015. EISA 2007 directed Federal agencies to purchase Energy Star and Federal Energy Management Program (FEMP)-designated products.
EO 13514 Federal Leadership in Environmental, Energy, and Economic Performance- 2009	This EO https://www.fedcenter.gov/programs/eo13514/ requires agencies to: • Appoint senior sustainability officer • Establish GHG-emission baseline for FY2008; set GHG-emission targets for FY2020 • Create strategic sustainability performance plan to document the plan to progress toward achieving FY2020 goals • Inventory and report its GHG emissions for previous FY
EO 13693 – Planning for Federal Sustainability in the Next Decade-2015	EO 13693 https://www.fedcenter.gov/programs/eo13693/ establishes a goal to reduce the Federal Government's GHG emissions by 40% during the next decade compared with 2008 levels. Additional sustainability goals of the EO include: • Increasing building energy efficiency • Increasing percentage of renewable energy in total energy usage • Increasing water use efficiency and management • Increasing fleet efficiency and eliminating non-essential fleet vehicles • Promoting sustainable acquisition and procurement • Advancing waste prevention and P2

Many of the materials used by NASA began to require new means of hazardous waste management, special permitting, and other special handling. Some materials were completely banned from manufacture and use. In some cases, manufacturers replaced or reformulated the materials to reduce impact from anticipated restrictions and regulations. Some of the replacement materials that were reformulated to meet the new environmental regulatory demands did not perform as well as the original formulations. NASA's stringent requirements for testing and qualification of materials and processes used on space hardware and for human space flight along with the relatively small demand for a specific product (in contrast to DoD, for example) make NASA especially vulnerable to a critical material loss.

As more environmental regulations and EOs began to focus on sustainability and energy efficiency, NASA was required to increase its use of renewable energy, increase efficiencies, and assess its approach to sustainability and critical infrastructure resiliency.

Requirements are also contained in NASA Policy Directive (NPD) *NASA Environmental Management* (NPD 8500.1), NASA Procedural Requirement (NPR) *NASA Energy Management Program* (NPR 8750.1), and the *2016 NASA Strategic Sustainability Performance Plan* (https://www.nasa.gov/agency/sustainability/sspp.html).

2.2 Objectives

The TEERM Principal Center (and its predecessor organization AP2) was established to help mitigate environmentally-driven risks to NASA's mission. TEERM identified and validated environmental and energy technologies through joint activities that enhance NASA mission readiness and reduce risk while minimizing duplication and associated costs. TEERM's objectives were to:

- serve as an integration activity to help improve NASA's ability to adopt new environmental and energy technologies to reduce unacceptable mission risks in a more proactive and cost-effective manner, and to better position itself to respond to new global regulatory and business paradigms;
- foster collaboration on projects to reduce duplication of effort and technology validation costs; and
- ensure that project results are applicable to current and future NASA programs.

As the risks and resulting impacts changed over time, TEERM and AP2 evolved to address these changes and protect the NASA mission. The initial AP2 focus was P2. SSP had early concerns related to the phase out of ODSs, including CFC-11, HCFC-141b, and TCA. This SSP concern helped shift the focus to mission risks including materials obsolescence. After the Space Shuttle retirement, TEERM shifted emphasis to include energy efficiency and facility resiliency projects to reduce cost and risk for NASA. TEERM continued various materials replacement projects of importance to the NASA Ground Systems Development and Operations Program (GSDOP), the NASA Space Launch System (SLS), DoD, and ESA.

3 Technology Evaluation for Environmental Risk Mitigation History

NASA Headquarters (HQ) established TEERM in 2007 at Kennedy Space Center (KSC), Florida as a refocusing of the AP2 Program Office established in 1998. Several early organizations played a role in TEERM development, including the Joint Group on Pollution Prevention (JG-PP), the Shuttle Environmental Assurance (SEA) Initiative, and the Centre for Pollution Prevention Program (C3P). The following section describes the role of these teams in TEERM evolution.

3.1 Joint Group on Pollution Prevention and the Acquisition Prevention Program

In 1994, the DoD’s Joint Logistics Commanders chartered a new group called the Joint Group on Acquisition Pollution Prevention (JG-APP) to coordinate joint service P2 activities. In 1998, JG-APP was merged with the Joint Policy Coordinating Group on the depot maintenance P2 efforts to create the JG-PP. At that same time, NASA and the Defense Logistics Agency (DLA) became members of JG-PP (Figure 1).

Figure 1. *JG-PP included NASA and DoD.*

The objective of JG-PP was to establish a process for jointly demonstrating and validating environmental technologies to mitigate cost and risk. This partnership focused on reducing P2 costs by identifying alternatives, defining common test protocols and acceptance criteria for alternatives, and performing laboratory and field-testing to qualify alternatives (Hill, 2001). The goal was to reduce or eliminate the use of hazardous materials in weapon system manufacturing and remanufacturing/maintenance processes.

Alternatives were identified and implemented using a validated JG-PP Methodology. Stakeholders applied a six-phase approach to implement material and process changes to reduce hazardous materials (Figure 2). Cooperation identified shared opportunities, common qualification requirements, and reduced duplication of effort.

In 1998, NASA created the AP2 Program Office located at NASA’s Kennedy Space Center (KSC). A formal Memorandum of Agreement (MOA) was signed in September 2004. AP2 focus was to reduce or prevent pollution, initiate partnerships for testing, and research new technologies. AP2 was created to help individual NASA centers and programs work together to evaluate and adopt environmentally-preferable technologies and practices. NASA chaired the JG-PP in its inaugural year.

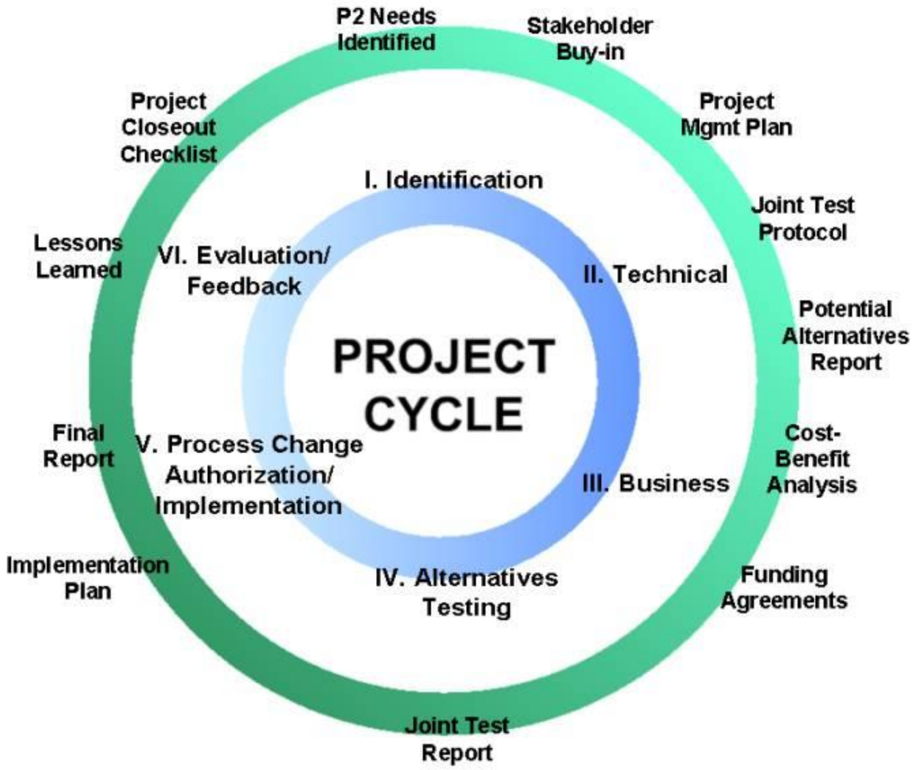


Figure 2. *JG-PP and AP2 methodology and products (Lewis, 2008a).*

Initial AP2 efforts focused on Pollution Prevention Opportunity Needs Assessments (PPONA) at NASA centers (Section 7.1), involvement with JG-PP projects and other DoD teams, and results dissemination of project findings to the NASA technical community.

Over time, AP2 began to develop its own projects focused primarily on NASA. AP2 also become more actively involved in government teams outside of JG-PP, such as the Joint Cadmium Alternatives Team and Joint Service Solvent Substitution Working Group. AP2 worked to develop partnerships within NASA as well as with outside entities. Partnerships helped AP2 extend its impact and fulfill its mandate of reducing or eliminating hazardous materials within NASA manufacturing and maintenance processes.

The TEERM approach to projects was based on the approach developed by JG-PP. Like the JG-PP process, AP2's process incorporated various acquisition reform approaches from the DoD, including Single Process Initiative, Acquisition Pollution Prevention Initiative, greater use of performance and commercial specifications and standards, and partnering with industry. The structured six-phase methodology guided stakeholders through the process of identifying hazardous materials to be reduced or eliminated, identifying critical and technical performance requirements, and securing commitments for testing and other analyses.

NASA (through AP2 and later TEERM) was an active partner in a number of JG-PP projects and again accepted leadership of JG-PP from 2007 to 2009. JG-PP was gradually replaced by other collaborative teams and ceased operations in 2010. AP2 collaborated on several JG-PP projects including, but not limited to:

- Non-Chrome Primers for Aircraft Exteriors (Section 7.4)
- Non-Chrome Aluminum Pretreatments (Section 7.4)
- Low/No VOC Coating System for Support Equipment (Section 7.4)
- Non-ODC Oxygen Line Cleaning (Section 7.5)
- Portable Laser Coatings Removal (Section 7.5)
- Lead-Free Solder Testing for High Reliability Electronics (Section 7.6)

Other AP2 projects of note included:

- Isocyanate Urethane Replacements on Structural Steel (Section 7.4)
- Alternatives to High VOC Chrome Coatings for Aircraft Exteriors (Section 7.4)
- Parts Washer Guidance Document (Section 7.5)

In 2003, AP2 began co-hosting an annual technical workshop with major European partners (C3P, ESA). This workshop has facilitated the exchange of technical information and helped identify new project opportunities partnerships. Section 5 describes the workshop in more detail.

3.2 Shuttle Environmental Assurance Initiative

As NASA began to identify mission risks associated with an increase in environmental regulations, NASA stood up several teams to mitigate these risks. Early teams included NASA Operational Environment Team, NASA Materials Replacement Technology Team, and Shuttle Replacement Technology Team (SRT2).

In 1995, the SRT2 was established as a forum for technical data exchange within the Space Shuttle community related to materials replacement. SRT2 included materials engineers from the individual SSP projects, NASA centers, SSP contractors, Environmental Health and Safety offices, and logistics. The initial impetus for this collaborative team was the Montreal Protocol and the need to replace TCA, CFCs, and eventually HCFC-141b. These materials were all used in critical applications on the Shuttle (Figure 3). SRT2 also began to track new regulations with the potential to affect SSP operations and began to evaluate replacements for CrVI in coatings.

The routine information sharing promoted by the SRT2 paved the way for future collaborative replacement technology efforts within the SSP. Established in 2000, the SEA replaced SRT2. SEA provided a more formal structure to the collaborative team and reported to Space Shuttle Management at Marshall Space Flight Center (MSFC). The SEA membership included a cross-functional team of environmental, materials, and logistics experts from SSP and the NASA centers, and represented one of the few such teams working in collaboration with SSP elements.

SEA used a formal risk management approach to identify, communicate, and mitigate environmentally-driven materials obsolescence issues for the SSP. SEA provided identification and communication of SSP-related environmental, health, and safety risks; environmentally-driven materials obsolescence issues; material replacement coordination; and efforts to realize resource efficiencies in mitigating issues.

AP2 and later TEERM was an active member of the SEA Team. AP2 reported on JG-PP projects of interest to the SSP. The AP2/JG-PP work on lead-free electronics led SEA to identify this as a major risk for the SSP. SEA team members were stakeholders and partners in AP2 and TEERM projects and were a resource for AP2 and TEERM to help identify and prioritize mission risks to NASA as well as serve as a conduit to NASA centers, contractors, and other technology teams such as the Aerospace Chromium (and Cadmium) Elimination Team (ACE).

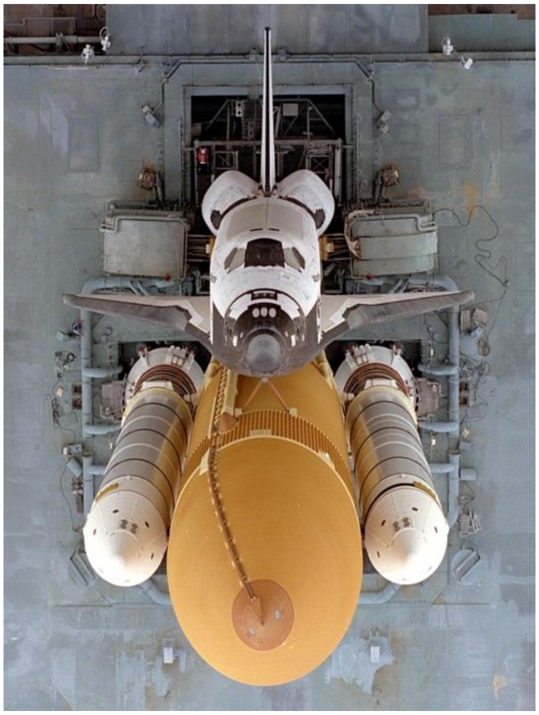


Figure 3. *Space Shuttle stack.*

The SEA focus on risks to mission represented primarily by material obsolescence (ODSs, CrVI, and Lead in Electronics) helped NASA decide to refocus AP2 from a P2 emphasis to a mission risk focus as TEERM (Section 3.4). SEA helped TEERM gather data on use of hazardous materials within NASA, specifically CrVI primer and lead-free solder use. SEA also occasionally identified materials being phased out by manufacturers.

3.3 Centre for Pollution Prevention Program

By the mid-2000s, environmental regulations in the U.S. were beginning to impact the availability of materials critical to NASA processes. The EU began the development of a new regulatory framework (REACH) that had the potential to affect the NASA mission by affecting critical materials availability in the global marketplace.

NASA realized the value of becoming proactive instead of reactive to changes in EU directives and laws that could impact its ability to procure critical materials. NASA began to focus on partnering in international collaborative opportunities and gaining support in staying abreast of EU environmental directives that could affect NASA and the U.S. in the global market.

To expand its international partnerships, NASA embarked on developing a relationship with Portugal and through Portugal with the EU. The C3P is an international organization that facilitates partnerships between Portuguese, European and United States governments, industries and other governmental agencies for identifying and integrating P2 solutions, practices and procedures. The C3P is recognized by the Portuguese Ministry of Environment, and NASA per the *Joint Statement between NASA and the Portuguese Ministry of the Environment Regarding Cooperation in the Field of Environmental Pollution Prevention Matters*, first signed on September 18, 2002. C3P is comprised of: The Institute for Welding and Quality (ISQ), Portugal; the Institute of Science and Innovation in Mechanical and Industrial Engineering

(INEGI), Portugal; and ITB, a U.S. company headquartered in Dayton, Ohio and founded by a Portuguese native. ISQ and INEGI support the identification of needs and technologies across Portugal and Europe and provide alternative materials, identification of potential technologies, and demonstration/validation testing. ITB provides additional engineering and technical support. TEERM is the primary U.S. government interface to C3P.

The mission of C3P, like AP2 and TEERM, is to foster innovation by identifying and validating environmentally sustainable technologies that reduce or eliminate hazardous materials or processes. Through joint activities, C3P projects reduce risk while minimizing duplication of effort and associated costs.

C3P helped facilitate partnerships with the U.S., the EU, industries, universities, and other Government agencies. C3P and NASA initiated an annual international workshop to encourage these relationships and projects (Section 5).

C3P projects in coordination with TEERM included a non-chrome coatings project initiated with two Portuguese entities, TAP Portugal (the Portuguese national airline) and the Aeronautical Industry of Portugal (OGMA), to target the reduction of CrVI, cadmium, and VOCs in aircraft maintenance operations (Section 7.4).

3.4 Technology Evaluation for Environmental Risk Mitigation

The AP2 Program Office initially focused on P2 as its primary means of supporting the mission. Over time AP2 began to focus more on risks to mission; on promoting more efficient systems and processes while ensuring the health and safety of people, assets, and the environment; and on providing technology evaluation and implementation.

In 2007, the AP2 Program was renamed the Technology Evaluation for Environmental Risk Mitigation Principal Center and was incorporated into a newly signed MOA between NASA HQ and KSC. This new name emphasized the purpose of the office (Environmental Risk Mitigation), not just P2, and how the team accomplished that goal (Technology Evaluation).

TEERM's technical focus was now beyond P2 and included any activities that mitigate environmental- and energy-driven risk to NASA's mission. Examples include lead-free solders, solvent-containing coatings and cleaners, and energy conservation goals. TEERM became increasingly focused on obsolescence and other risks to mission during its close involvement with the SEA team and later interfaces with the Constellation Program (CxP) and the SLS.

NASA's participation in JG-PP ceased with JG-PP dissolving in 2010 and participation in NASA's SEA group ceased in 2012 with the Space Shuttle retirement. Loss of these two teams as collaborative partners required TEERM to focus on maintaining existing relationships and establishing new ones. TEERM continued work on materials replacement projects but the new SLS Program was not focused on long-term obsolescence risks and therefore was not a viable partner in risk mitigation.

In 2012, a new MOA was signed between NASA HQ and KSC to continue TEERM. TEERM project involvement and partnerships continued to broaden including new and expanded partnerships within the DoD [notably U.S. Navy Air Systems Command (NAVAIR) and Naval

Facilities Engineering Command (NAVFAC)], other U.S. Federal Agencies [notably Department of Energy (DOE)], and internationally (formal agreement with ESA). Projects began to involve more international partners.

TEERM efforts also began to emphasize reimbursable and negotiated in-kind contributions in addition to funding from NASA HQ EMD [Environmental Compliance and Restoration (ECR)]. There was increased coordination with the KSC Corrosion Technology Laboratory [(CTL) https://corrosion.ksc.nasa.gov] especially for testing services.

With new EOs (EO 13514 and EO 13693) NASA faced new energy and sustainability requirements; and TEERM responded with an increase in energy, sustainability and infrastructure projects and partnerships. TEERM was EMD's technology assessment arm, so TEERM's portfolio grew to include various green engineering projects in support of initiatives at NASA centers.

TEERM program success was tied to the number of active demonstration projects, projects which TEERM largely generated and found funding for itself. Proposed projects had to be cost justified and clearly capable of reducing mission risk. Appendix C shows major milestones in TEERM evolution. This Compendium Report in following sections describes in greater detail the development of important partnerships and projects listed. The following section outlines the TEERM process approach including the importance of stakeholders' contributions and how TEERM leveraged direct and in-kind support from partners outside of EMD.

4 Technology Evaluation for Environmental Risk Mitigation Approach

The NASA HQ TEERM Lead and NASA TEERM Manager at KSC provided centralized leadership for the program. ITB provided technical and engineering support.

TEERM projects and integration activities were designed to evaluate, in an unbiased fashion, technological solutions to environmentally-driven risks impacting NASA customers. TEERM project technology areas included, but were not limited to:

- Materials Management and Substitution
- Recycling and Pollution Control Strategies
- Renewable and Alternative Energy
- Green Sustainable Development

4.1 Project Approach

A fundamental activity of TEERM was the testing and validation of technologies that could potentially reduce environmentally-driven risks to NASA's mission. Testing of such materials or processes is necessary to obtain data on their performance prior to implementation.

TEERM applied the approach developed by JG-PP and AP2 (refer to Figure 2). The project management process identified risks to NASA mission and cultivated relationships that benefitted the entire project lifecycle, from risk assessment to project execution.

4.1.1 Opportunity Assessment and Partner Commitments

TEERM identified potential risks to the NASA mission and evaluated drivers for that risk that were driven by regulations, market forces, and federal requirements. TEERM evaluated risks and impacts to the NASA mission using a qualitative risk matrix approach consistent with standard practice. Potential risks were assessed based on likelihood and consequence of the risk condition.

Project formulation was central to TEERM's approach and success. Defining the problem and being able to communicate how the problem relates to the various stakeholders/partners proved critical in acquiring the partners' contributions, either direct or in-kind support. Steps in the planning of a TEERM project included:

- Identify stakeholders
- Formulate team
- Identify technical requirements
- Identify and screen potential solutions
- Secure resource commitments through formal and informal agreements

The early and effective matching of a solution to a need is important. The technology scouting process began by TEERM building and using its network of end-users and experts to identify needs. Next, TEERM identified and assessed new technologies that could offer a potential solution. Then, TEERM introduced the potential alternative(s) to the end-users for consideration. In some instances, the proposed solution was mature enough that the end user could implement the solution with little more than a demonstration. In other cases, extensive laboratory or field testing was required, in which case TEERM would attempt to formulate a project team of stakeholders.

TEERM projects commonly involved two or more NASA stakeholders in the planning and execution of laboratory testing or field demonstrations. Once testing began, partners shared the testing cost, in certain cases by conducting some of the testing at their facility as an “in-kind” contribution to the project.

4.1.2 Project Execution

Project execution included the demonstration/validation work, data analyses, and report writing, encompassing the following tasks:

- Coordinated technology demonstration and testing
- Analyzed data and determined acceptability
- Prepared and disseminated reports
- Monitored implementation

Major documents produced during the life of a project included:

- ***Joint Test Protocol (JTP)*** – Documented critical technical and performance requirements that an alternative material or process must meet to be considered acceptable.
- ***Potential Alternatives Report (PAR)*** – Documented viable alternatives, the down-selection process, and alternatives ultimately recommended for testing/ implementation.
- ***Cost Benefit Analysis (CBA)*** – Documented analysis of economic feasibility of the potential alternatives as compared to the current (baseline) material/ process.
- ***Joint Test Report (JTR)*** – Documented testing and test results and provided analysis and conclusions.

TEERM adopted the titles and structure of these reports from JG-PP.

4.2 Partners and Stakeholders

In executing technology evaluation projects, TEERM interfaced and collaborated with other agencies, both domestic and international. Partnering provided collaborative opportunities for engineers within the global science community and maximized the scientific value of any engineering activity while minimizing costs. Additionally, partnering provided access to information needed for validation under a broad range of conditions. European partnerships helped NASA engineers stay abreast of European environmental directives that affected NASA as well as their project involvement in the U.S. and global markets (NASA, 2006; Lewis and Valek, 2010).

This collaborative approach to solving environmental and energy problems benefitted project members in multiple ways:

- Resources were shared, which reduced the cost to test and qualify alternatives.
- Technical confidence in alternatives identified and tested was increased.
- Overall effort technical quality was improved through knowledge sharing.
- Implementation of qualified alternatives was accelerated.

Testing of materials, such as environmentally-preferable coatings and cleaning/depainting technologies, can cost hundreds of thousands of dollars. Individual NASA centers or programs usually cannot fulfill all demands to pay for this testing. Through collaboration and financial commitments from project stakeholders and third-party sources, funding expensive demonstration/validation efforts was possible.

TEERM also provided NASA representation to environmental and energy entities outside of NASA. Within the U.S., TEERM worked with the U.S. DoD qualifying new materials and processes to reduce or eliminate hazardous materials in Army, Navy, Air Force, Marine Corps, and NASA applications. TEERM worked very closely with Air Force Space Command (AFSPC) on projects to improve the environmental sustainability of space launch facilities.

TEERM interfaces included domestic and international government and private organizations (Appendix D). Examples of entities with whom ITB engaged include:

- ***NASA*** – KSC, MSFC, Jet Propulsion laboratory (JPL), Ames Research Center (ARC) Glenn Research Center (GRC), Goddard Space Flight Center (GSFC), White Sands Test Facility (WSTF), Johnson Space Center (JSC), Wallops Flight Facility (WFF), NASA Recycling and Sustainable Acquisition (RSA) Principal Center, NASA Regulatory Risk Analysis and Communication (RRAC) Principal Center
- ***Other U.S Government*** – Air Force, Army, Navy, Marine Corps, DOE - National Renewable Energy Center (NREL), Sandia National Laboratories (SNL), Defense MicroElectronics Agency (DMEA), DLA, EPA, Florida Power and Light (FPL)
- ***International*** – BAE (United Kingdom), C3P, ISQ, OGMA, Swedish Space Corporation, ESA, Bavarian Government, Norwegian Government, Guiana Space Centre in Kourou, KTH Royal Institute of Technology in Sweden, GE Global Research (Munich, Germany), Kongsberg Satellite Services (KSAT), Celestica, Nihon Superior
- ***Industry*** – AECOM, Alliant Techsystems (ATK), Raytheon, Boeing, Rockwell Collins, BAE Systems, Lockheed Martin, Harris, Honeywell, L3 Technologies (L3), GE Global Research (U.S.), Lockheed Martin, Delaware-North [KSC Visitor Complex KSCVC) contractor], NextEra Energy Resources, United Launch Alliance, United Space Alliance (USA), University of Dayton Research Institute
- ***Academia*** – University of California at San Diego, University of Central Florida, University of Florida, University of Dayton Research Institute (UDRI), University of Alaska, University of Maryland, Portland State University, Yale University, University of Massachusetts Lowell, New Jersey Institute of Technology, Rochester Institute of Technology

TEERM/AP2 facilitated the signing of formal agreements between NASA and outside agencies to cooperate on matters of shared interest (Table 2). TEERM also facilitated NASA's acceptance of approximately 20 Military Interdepartmental Purchase Requests (MIPRs) from the DoD for various efforts, including coatings for launch facilities and lead-free electronics (Appendix E).

Table 2. *TEERM/AP2 facilitated formal partnership agreements.*

NASA Partner	Agreement	Purpose
Portuguese Ministry of Environment (2002 and 2012)	Joint Statement Between NASA and the Portuguese Ministry of the Environment Regarding Cooperation in the Field of Environmental Pollution Prevention Matters and Terms of Reference Concerning Cooperation on Environmental Pollution Prevention Matters, both signed September 18, 2002 and renewed 2012	Explore proposals on cooperation in environmental matters.
C3P	Agreement between NASA and C3P on sustainable construction practices and technologies. signed October 13, 2010	Exchange data and information necessary on new technologies and practices that will become new building design templates for sustainable construction.
ESA	Agreement between NASA and ESA, signed June 21, 2011	Establish a common understanding for coordination of activities to identify, evaluate, and test promising commercially-available coatings as potential replacements for CrVI coatings for various aerospace applications.
ESA	MOU between NASA and ESA Concerning Cooperation in the Field of Space Transportation, signed September 11, 2009	Exchange data and information to alleviate concerns with potential obsolescence of materials/processes involving HazMats.
ESA	Cooperative Agreement: Title: Implementation Plan on Environmentally Friendly Substances for Stainless Steel Alloy Passivation and Coatings for Launch Facilities and Ground Support Equipment Country: ESA Execution Date: November 12, 2014	NASA and ESA will cooperate in the areas of 1) validating use of citric acid as environmentally-preferable material to nitric acid for passivation of stainless steel alloys and 2) evaluating commercially available environmentally-preferable coatings for maintenance of launch facilities and Ground Support Equipment (GSE).
SNL	Bailment Agreement between NASA KSC and SNL, signed 2011	Operational testing of a Hydrogen Fuel Cell Mobile Lighting Tower at NASA KSC
DOE/ NREL	Interagency Agreement signed January14, 2014 (for 2 ½ yrs., 2014 – 2016)	NREL funded wind and green roof instruments and installation.

Details of TEERM/AP2 projects discussed in Sections 7 and 8 show the extent of TEERM's relationships with partners as well as the benefits of these partnerships in data sharing, access to Subject Matter Experts (SMEs), and direct and in-kind support to projects. The following list summarizes major partnerships and the benefits to NASA:

- NASA
  - *NASA KSC GSDOP (formerly 21st Century Launch Complex)* – provided $1.3M for management and testing on three TEERM projects related to new, environmentally-preferable materials on launch structures and GSE.
  - *KSC CTL* – performed much of the materials and corrosion testing.

- **DoD**
  - Services comprising JG-PP were major contributors to the planning, funding, and management of projects in the early (AP2) years.
  - Later, the Air Force and Navy were major contributors to the planning and direct funding for several projects that TEERM managed for those Services.
- **European**
  - C3P provided project integration, partnership and project development, and workshop support.
  - ESA provided project planning, in-kind contributions to project testing, and workshop support.
- **Industry**
  - Performed most of the testing, accounting for most of the in-kind contributions throughout the years.

4.3 Outreach and Data Dissemination

ITB disseminated government-approved TEERM testing data, and routinely prepared and submitted technical papers, articles, and presentations to conferences, workshops, journals, and other venues to gain visibility for TEERM products. One of the more prominent methods used by TEERM to share information was NASA and inter-agency working groups (Appendix F). This engagement with teams inside and outside NASA allowed TEERM to make presentations on TEERM projects, identify the need for new projects, and develop relationships with SMEs in government and industry.

Conferences and workshops also played prominently in TEERM's outreach. Project managers frequently presented results on TEERM hexavalent chromium alternatives projects and lead-free electronics projects at major national environmental and electronics conferences. Most of TEERM's presentations were published in the proceedings from the conferences. Internationally, the International Workshop initiated with C3P and AP2 in 2003 was a major vehicle for AP2/TEERM annual outreach, dissemination of information, and development of relationships and new collaborations. Section 5 describes these workshops and their benefits to NASA.

TEERM occasionally published articles in technical magazines, as well.

- Article in the KSC *Spaceport News* features TEERM's support to KSC's GSDOP.
- Article on low VOC coatings for NASA *TechBriefs* (August 1, 2010, http://www.techbriefs.com/component/content/article/tb/tech-exchange/nasa-tech-needs/8273).
- Defranco, Kessel, et al., 2017. "Evaluation of Hexavalent Chromium Free Bond Primers for Aerospace and Defense Applications". In *Products Finishing.*
- Kessel, K., 2017. "Replacing Hexavalent Chromium in Pretreatments for Aerospace Applications". In *Products Finishing*.

TEERM regularly used NASA electronic resources for data dissemination. Many TEERM technical reports (JTPs, JTRs) and technical briefings, including this Compendium, are available to NASA employees and contractors through NTRS (https://www.sti.nasa.gov/). TEERM also published an annual newsletter, QuEST: Qualifying Environmentally Sustainable Technologies (Figure 4), that is also available on NTRS.

Before TEERM ended, all TEERM newsletters and many TEERM technical reports and presentations were available to the public via the TEERM website (no longer active).

Figure 4. *TEERM published an annual newsletter.*

5 International Workshop

5.1 Workshop Overview

Since 2003, TEERM has supported an annual collaboration with European partners to hold a workshop for technical interchange and to help identify new project opportunities. Co-sponsors have included C3P and ESA. U.S. locations have served as host in even-numbered years, and international locations have served as host in odd-numbered years.

The predecessor to the first workshop was a 2002 technical interchange meeting between AP2 and C3P in London focused on lead-free solder. The success of this meeting led to a more formal workshop in 2003 with a broader scope. Table 3 lists the locations and number of attendees for each of the 15 workshops.

Beginning in 2005, NASA and European partners funded students to attend the workshops and participate by giving oral and poster presentations on their academic research. Through the years, NASA has sponsored more than 20 students to attend, ESA more than 10 students, and organizations such as the Luso-American Development Foundation (FLAD) have sponsored more than 30 Portuguese students.

TEERM coordinated with project sponsors, developed agendas, and managed the complicated logistics required for each international workshop. Over the 15 workshops, TEERM delivered 32 presentations on TEERM projects. Presentations made by the TEERM team are available on the NTRS (https://www.sti.nasa.gov/).

Table 3. *International workshops.*

Year	Dates	Title	Location	Attendance	Major Events and Comments
2003	September 19	C3P and NASA TECHNICAL WORKSHOP "Integrating Common Problems for Shared Solutions"	Technical University of Lisbon Lisbon, Portugal	122	• Protocol Signing Ceremony – Cooperation and Technical Exchange Agreements were signed among C3P and OGMA, TAP-Air Portugal, National Association of Electric and Electronic Manufacturers, Caetano Bus (car/bus manufacturers) and British Aerospace Systems. • Event attended by Portuguese Minister of Environment, American and British Ambassadors, and Ambassador Secretary General of the Ministry of Foreign Affairs of Portugal.
2004	September 22–23	2004 NASA-C3P INTERNATIONAL P2 WORKSHOP	Radisson Resort Cape Canaveral, FL	115	• First workshop involving adjunct project/technical meetings. Helped increase number of attendees and leverage their participation.
2005	September 8–9	2005 C3P AND NASA TECHNICAL WORKSHOP "Partnering for Shared Solutions to Common Environmental Problems"	Catholic University of Portugal Lisbon, Portugal	133	• Workshop sponsorship from the Catholic University of Portugal. • Notable speakers: Prof. Humberto Rosa, Secretary of State for the Environment, Portugal; Addriene O'Neil, Charge d' Affaires of U.S. Embassy, Portugal; Aaron Ram, Ambassador of Israel in Lisbon • Financial support provided by Luso-American Foundation for Development and Office of Naval Research Global (ONRG). • Israeli Users Association of Advanced Technologies in Electronics (ILTAM) signed a Cooperation Protocol with C3P.
2006	November 1–2	2006 INTERNATIONAL WORKSHOP ON POLLUTION PREVENTION AND SUSTAINABLE DEVELOPMENT	Cheyenne Mountain Resort Colorado Springs, CO	130	• Workshop sponsorship from HQ AFSPC. • Notable speaker: Col. Shawn Jansen, Director of the Commanders Action Group, HQ AFSPC. • Adjunct meetings: NASA SEA and Air Force Corrosion. • Hydrogen safety training was provided by representatives from NASA WSTF.
2007	November 7–9	2007 C3P and NASA TECHNICAL WORKSHOP "Partnering for Energy and Environmental Stewardship"	School of Tourism and Maritime Technology Peniche, Portugal	243	• Expanded to three-day workshop, with additional topics (remediation, renewable energy). • Spike in number of attendees driven by students from hosting university. • Notable speakers: Alfred Hoffman, U.S. Ambassador in Lisbon; Prof. Humberto Rosa, Secretary of State for the Environment, Portugal (by video).

Year	Dates	Title	Location	Attendance	Major Events and Comments
2008	November 18–20	NASA/C3P-2008 INTERNATIONAL WORKSHOP ON POLLUTION PREVENTION AND SUSTAINABLE DEVELOPMENT "Enhancing Mission through Proactive Environmental Risk Mitigation"	University of California San Diego San Diego, CA	101	• First workshop with student research presentations. • Workshop sponsorship from University of California San Diego (UCSD). • Notable speaker: Prof. Humberto Rosa, Secretary of State for the Environment, Portugal (by video). • Organized meetings and tours of five locations for officials from Torres Vedras, Portugal.
2009	November 10–13	2009 INTERNATIONAL WORKSHOP ON ENVIRONMENT AND ALTERNATIVE ENERGY "Global Collaboration in Environmental and Alternative Energy Strategies"	GE Global Research Center Europe, Garching/Munich, Germany	80	• First European workshop held outside of Portugal. • Notable speaker: Conrad Tribble, U.S. Consul General to Munich. • Workshop sponsorship from GE Global Research. • Students and professors from three universities. • Six student presentations.
2010	November 2–4	2010 INTERNATIONAL WORKSHOP ON ENVIRONMENT AND ENERGY "Global Collaboration in Sustainable Environmental and Alternative Energy Strategies"	University of California San Diego San Diego, CA	85	• Workshop sponsorship from UCSD, with support from Sanyo and General Atomics. • Notable speaker: Prof. Humberto Rosa, Secretary of State for the Environment, Portugal (by video). • 14 student presentations.
2011	November 15–18	2011 INTERNATIONAL WORKSHOP ON ENVIRONMENT AND ALTERNATIVE ENERGY "Global Collaboration in Sustainable Environmental and Alternative Energy Strategies"	The European Space Research and Technology Centre (ESTEC) Noordwijk, The Netherlands	116	• First workshop fully co-sponsored by ESA. A full day was dedicated to a student session. • 17 student presentations.
2012	December 4–7	2012 INTERNATIONAL WORKSHOP ON ENVIRONMENT AND ALTERNATIVE ENERGY "Enabling Sustainable Space Exploration"	NASA GSFC, Greenbelt, MD	106	• Eight countries were represented at the workshop. • 11 student presentations.

Year	Dates	Title	Location	Attendance	Major Events and Comments
2013	November 18–21	2013 INTERNATIONAL WORKSHOP ON ENVIRONMENT AND ALTERNATIVE ENERGY "Increasing Space Mission Resiliency through Sustainability"	The ESA Centre for Earth Observation Frascati, Italy	70	• First workshop to emphasize resiliency as an overarching theme. • 17 student presentations.
2014	October 21–24	2014 INTERNATIONAL WORKSHOP ON ENVIRONMENT AND ALTERNATIVE ENERGY "Increasing Space Mission Resiliency through Sustainability"	KSCVC KSC, FL	150	• 17 student presentations. • 15 nationalities were represented at this workshop.
2015	November 10–13	2015 INTERNATIONAL WORKSHOP ON ENVIRONMENT AND ALTERNATIVE ENERGY "Increasing Space Mission Ground Infrastructure Resiliency through Sustainability"	The ESA's European Space Astronomy Centre (ESAC) Madrid, Spain	81	• Several desirable interactions occurred among presenters and attendees, many resulting from informal discussions. • The student session participants were exceptional this year, interacting with presenters all week and contributing ideas for workshop improvements. • 12 student presentations.
2016	October 18–21	2016 INTERNATIONAL WORKSHOP ON ENVIRONMENT and ALTERNATIVE ENERGY "Increasing Space Mission Ground Infrastructure Resiliency through Sustainable Measures"	NASA JPL Pasadena, CA	60	• First workshop to involve multiple-facilitated breakout sessions. These new sessions resulted in follow-on activities incorporated in the 2017 workshop and in 2017 TEERM task orders. • 15 student presentations.
2017	May 30–June 1	2017 INTERNATIONAL WORKSHOP ON ENVIRONMENT and ALTERNATIVE ENERGY "Resiliency of Critical Infrastructure"	The ESTEC Noordwijk, The Netherlands	63	• The final workshop for which TEERM was involved in the workshop sponsorship. • 12 student presentations.

5.2 Workshop Evolution

TEERM sponsored the International Workshops from 2003 through 2017. During that time, the workshop's focus and attendance evolved in response to changes in the project portfolio of the AP2 and TEERM programs.

The initial workshop held in 2003 in Portugal was attended almost entirely by professionals from Portugal and the U.S. The next workshop in 2004 was held at KSC and had significant participation by NASA and the Air Force. These early workshops emphasized P2 needs and opportunities and mitigation of lead-free solder risks.

In 2005, TEERM managed its first workshop at a university, the Catholic University of Portugal in Lisbon. This workshop had broader international participation than previous workshops due in part to C3P's outreach efforts and international interest in TEERM's lead-free solder project. Portugal's Secretary of State for the Environment was a distinguished speaker. FLAD and ONRG were co-sponsors of the workshop. FLAD sponsored students at this event and continued to sponsor students for several more workshops.

The 2006 workshop was held in Colorado Springs with sponsorship and local logistical support from Headquarters AFSPC. SEA and the Air Force Corrosion Team held meetings at the conference hotel, which promoting increased workshop attendance by NASA and Air Force personnel.

The 2006 workshop had a newly added emphasis on renewable energy as a technical session topic, with audience members offering accolades for the workshop's renewable energy session. This success was fostered by the following joint NASA and C3P activities that occurred earlier in the year, including:

- Several meetings between NASA and C3P partners in Lisbon to discuss new project ideas in the field of renewable energy.
- A video conference between NASA WSTF, NREL, the U.S Embassy in Portugal, and International Science and Technology Center [INASMET (Spain)] to select areas of mutual interest and potential synergy between NASA, C3P and NREL in advanced renewable energy technologies.
- Meetings between representatives of C3P, NASA, and the Portuguese Secretary of State of Environment to present—and later initiate—a renewable energy project for Portugal's Berlenga Island.

The 2007 workshop, in Peniche, Portugal, was the second held at a university. This event is most distinguished by its more than 80-percent increase in attendance compared to previous TEERM-sponsored workshops. Holding the workshop at a university that actively promoted student participation in the workshop was a factor in the increased attendance, as more than 70 university students and professors attended. This unplanned success led to a change in all future workshops to include a place in the program for formal research presentations by university students.

The 2008 workshop was the first workshop held after the transition from AP2 to TEERM. As such, a focus of this and later workshops was on enhancing mission through proactive risk mitigation and sustainability. Other introductions were: presentations from ESA and university students; presentations on regulations and directives with global impact, such as REACH, RoHS, and WEEE; and a NASA panel discussion on incorporating elements of sustainability into a human lunar mission. In conjunction with the workshop, NASA and C3P orchestrated several side meetings for selected visitors from Portugal, the objective being to provide opportunities for sharing visions, lessons learned and potential collaborations in sustainability between Portugal and southern California entities.

By 2009, energy and sustainability became a theme of the workshop. This workshop, held in Garching/Munich, Germany, was the first held outside either the U.S. or Portugal. In addition to attendance by students from universities in the U.S. and Portugal, this workshop involved student presenters from two leading German universities.

By the 2010 workshop, NASA and C3P had agreed to collaborate on Portugal's ECOS (sustainable construction) project, and NASA and ESA had neared agreement to collaborate on studying alternatives to hexavalent chromium-containing coatings. As such, the topics of sustainable development and materials substitution in support of space operations drove much of the workshop agenda.

The 2011 workshop included an interesting panel discussion on the challenges of operating installations across borders, touching on issues such as conflicting EU and country regulations and the benefits of building partnerships across borders. By 2011, presentations of student research were an increasingly large and established part of the workshop, comprising a full day.

By 2012, the ability to protect critical energy systems from grid failures due to natural or man-made disruptions was of increasing importance to federal facilities and to TEERM's re-focused project development process. In response, a technical session on facility energy supply solutions for critical applications was added to the scope of the 2012 workshop held at NASA GSFC. This workshop was also characterized by a record-breaking participation of 17 oral/poster presentations in the student session.

The 2013 workshop at ESRIN in Italy expanded upon the critical infrastructure theme by including a full day of presentations on increasing critical ground infrastructure resiliency through sustainability and incorporating the issue of water security.

In 2014, the workshop returned to KSC for the first time in 10 years. Twenty-six students attended, of which approximately one-third were sponsored.

The 2016 workshop at NASA JPL was the first to involve facilitated breakout sessions as an aid to project development. A result of one of these sessions was the development of a water resiliency checklist. The checklist is a data request tool that includes approximately 70 questions about water source, treatment, storage, distribution, security, preparedness, and resiliency. The purpose of the checklist is to facilitate the collection of data necessary to characterize the conditions and issues associated with the surveyed water system and identify opportunities to improve security, preparedness, and resiliency. These sessions resulted in follow-on activities incorporated in the 2017 workshop at ESTEC.

The following list includes examples from several International Workshop agendas.

- **2003 C3P and NASA TECHNICAL WORKSHOP "Integrating Common Problems for Shared Solutions"**
    - Chemical Product Regulations Impact in Transatlantic Relations
    - VOC's Panel
    - Reduction/Elimination of Emissions CrVI Plating Baths
    - Lead-Free Solder
    - Heavy Metals in Aerospace Processing – Successes and Challenges
    - Technology Migration Opportunities: Low/No VOC Coatings/Oxygen Line Cleaning
    - Lead-Free Copper Zinc Alloys
    - Polymer Concretes

- **2008 NASA/C3P INTERNATIONAL WORKSHOP ON POLLUTION PREVENTION AND SUSTAINABLE DEVELOPMENT "Enhancing Mission through Proactive Environmental Risk Mitigation"**
    - Vision for Sustainability
    - Environmentally-Driven Risk Mitigation in Aerospace
    - Federal Sustainability Programs
    - Sustainability in Marine Ecosystems
    - Replacements for Chromium/HAPs/VOCs in Cleaning and Coatings
    - Replacements for Regulated Chemicals Lead in Electronics Renewable Energy
    - DoD/NASA Sustainable Approaches
    - REACH

- **2010 INTERNATIONAL WORKSHOP ON ENVIRONMENT AND ALTERNATIVE ENERGY "Global Collaboration in Sustainable Environmental and Alternative Energy Strategies"**
    - NASA's Vision of Sustainability
    - Role of Innovation in Sustainable Development
    - UCSD Student Presentations – Energy Technologies
    - Materials Management and Substitution Sessions
    - Remediation and Cleanup
    - Recycling and Pollution Control

- **2015 INTERNATIONAL WORKSHOP ON ENVIRONMENT AND ALTERNATIVE ENERGY "Increasing Space Mission Ground Infrastructure Resiliency through Sustainability"**
    - Energy Efficiency and Water Conservation
    - Infrastructure Resiliency Measures and Analytical Tools
    - Environmentally-Driven Changes to Aerospace Materials and Process Management
    - Corrosion Protection
    - REACH Regulation

- **2017 INTERNATIONAL WORKSHOP ON ENVIRONMENT AND ALTERNATIVE ENERGY "Resiliency of Critical Infrastructure"**
    - Sustainable Stakeholder Dialogue in Space Sector
    - Overview of ESA's Coordination Office on Sustainable Development
    - Earth Space Technical Ecosystem Enterprises (ESTEE) Solutions and Research and Development Initiatives
    - Digital Agenda for Space
    - Increasing Resilience and Sustainability of NASA and ESA Critical Infrastructure
    - Environmentally-Driven Challenges to Aerospace Materials and Process Management

5.3 International Workshop Benefits and Lessons

NASA is committed to the environment and the need for partnering in solving environmental problems, as evidenced by important NASA international partnerships over the last 15 years. The annual workshops planned and attended by TEERM helped strengthen these partnerships and enhance collaboration.

TEERM played a pivotal role in strategically designing the annual workshops to include: a balanced mixture of speakers from NASA, DoD, other U.S. federal agencies, ESA, academia, major aerospace and defense contractors, and technical solution providers; both technical professionals and students; and presentations on both problems and potential solutions. Annual workshops offered unique value to NASA by providing opportunities for attendees from across the globe to meet face-to-face to discuss environmentally-driven risks to their operations and potential mitigating solutions. As such, workshops served as an extension of TEERM's process for developing collaborative projects to cost-effectively validate new technologies. In addition, the execution of these workshops enabled TEERM to build a strong network of more than 1400 professionals, providing NASA with a method to effectively reach SMEs in areas of shared interest.

6 Technology Evaluation for Environmental Risk Mitigation Accomplishments and Benefits

6.1 Benefits

TEERM benefitted NASA by identifying and evaluating mitigation technologies that reduced risks to the NASA mission (obsolescence risks, human health and environmental risks, and infrastructure risks). TEERM developed risk and cost reducing projects, leveraged direct and in-kind funding from sources outside EMD, and developed and maintained international and domestic relationships and partnerships.

6.1.1 Projects

In the first several years of AP2, project efforts focused on supporting projects formulated and managed by organizations outside of TEERM, most notably JG-PP. In these projects, TEERM acted as a focal point for NASA, ensuring that the right NASA SMEs were involved, and critical NASA requirements were being incorporated in the project plans. While TEERM had an important role in these early collaborative projects, the program did not manage any of them. Later, however, TEERM began initiating and managing its own projects in collaboration with its expanding network of partners from DoD, DOE, ESA, and industry.

TEERM has managed 59 technology evaluation projects since 2005 geared to NASA applications. TEERM employed an independent, risk-to-mission process to assess 262 “green” solutions for NASA, of which ITB recommended 70 for implementation (Figure 5). Appendix B lists projects in which TEERM had a significant role. Only major projects or those tasks that contributed to major projects are discussed in this Compendium Report; however, Appendix B lists all projects in which TEERM played a substantial role.

TEERM developed risk and cost reducing projects and green technologies for handoff to other NASA programs and centers [KSC, JSC, Principal Center for Recycling and Sustainable Acquisition (RSA)]. Projects transferred to RSA and the KSC Environmental Solutions Partnership include bio-based asphalt restorative compound technology and technology that harvests invasive plant species and processes the material into a clean burning bio-gas.

6.1.2 Leveraged Resources

A cornerstone of TEERM is the leveraging of resources outside of EMD to support TEERM projects. TEERM leveraged $2.4M direct and almost $19M indirect funding from sources outside NASA EMD since FY2005 (Figure 6). By 2016, this resource leveraging resulted in a value ratio of 2.2 to 1 for TEERM projects. Organizations that provided direct and in-kind funding included the Environmental Security Technology Certification Program (ESTCP), AFSPC, Navy, NASA GSDOP, NREL, and ESA. These commitments from other NASA organizations and outside agencies allowed TEERM to complete projects that benefitted the NASA mission in a cost-effective way.

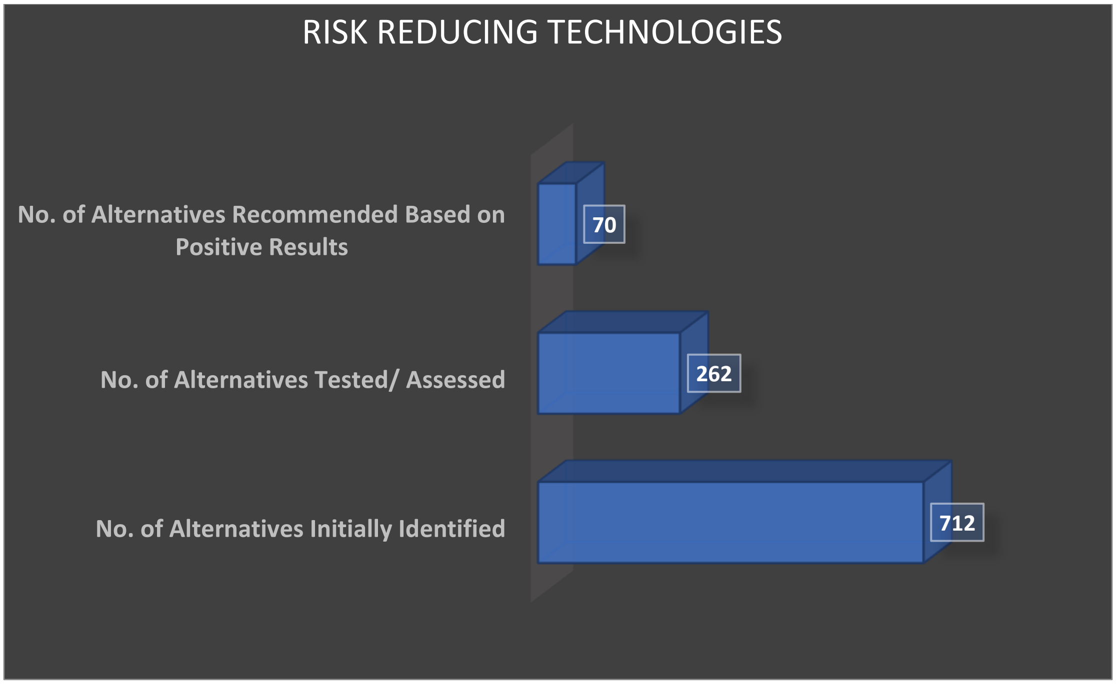


Figure 5. *Number of risk reducing technologies TEERM identified, evaluated, and recommended.*

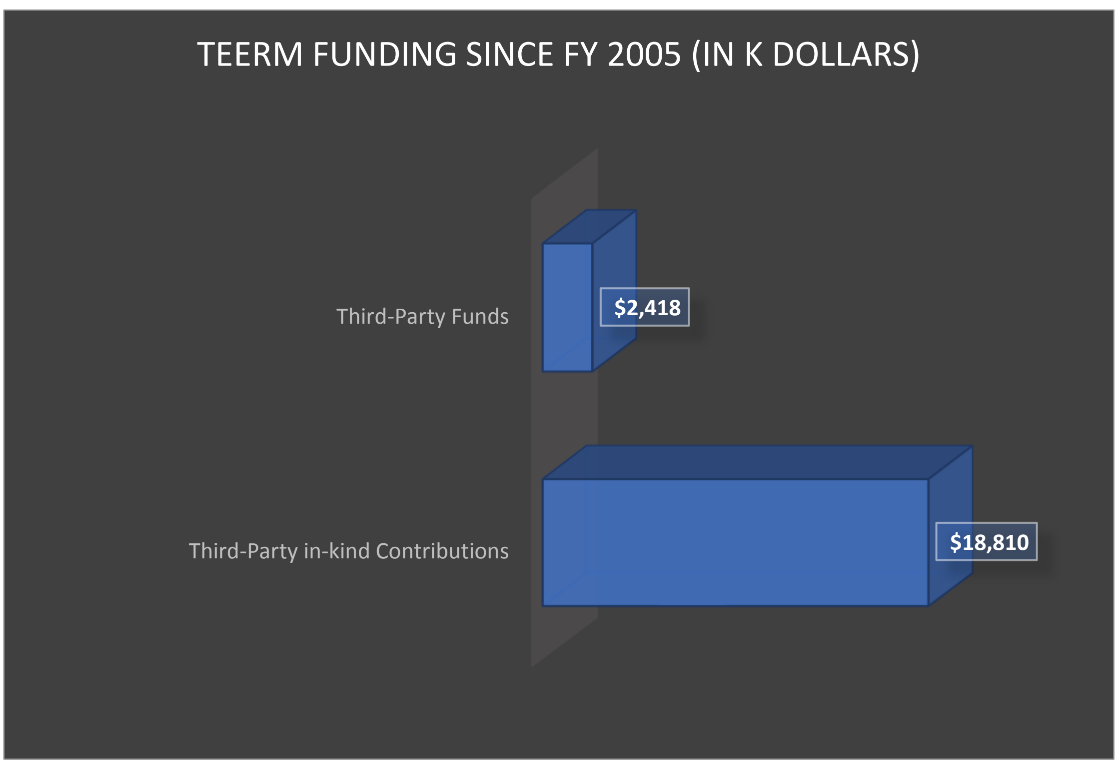


Figure 6. *TEERM leverages in-kind and direct funds from other organizations.*

6.1.3 Professional Network

TEERM developed international and domestic relationships and collaborative projects that provided NASA ready access to SMEs and project sponsors/partners. Organizations represented in TEERM's professional network include NASA, ESA, DoD organizations, NASA contractors, and representatives from other commercial entities (Figure 7a). TEERM's network includes contacts in 16 countries, including Portugal, Germany, France, Italy, Spain, Sweden, the Netherlands and the United Kingdom (U.K.) (Figure 7b).

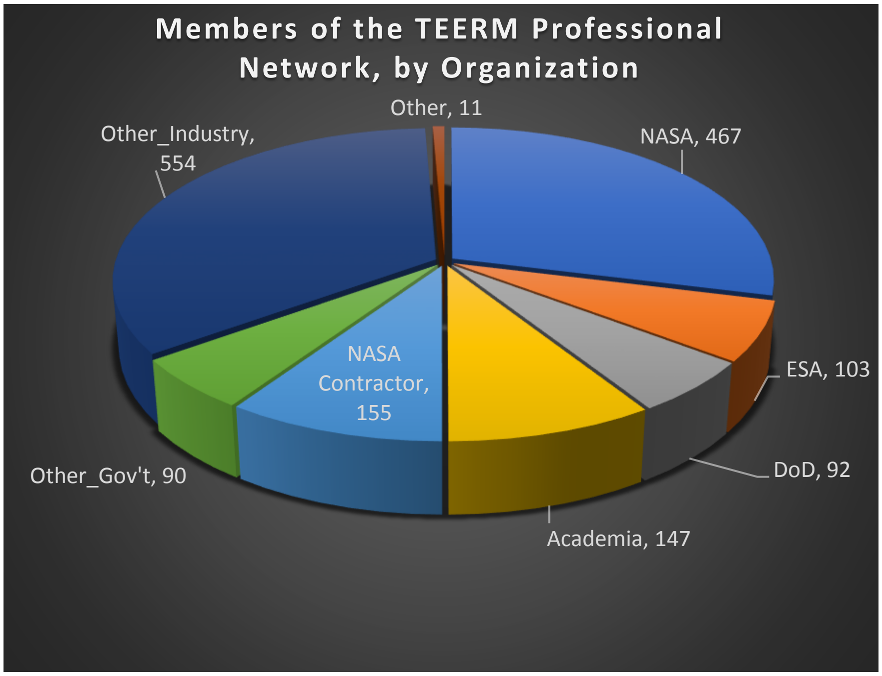


Figure 7a. *TEERM professional network – by organization*.

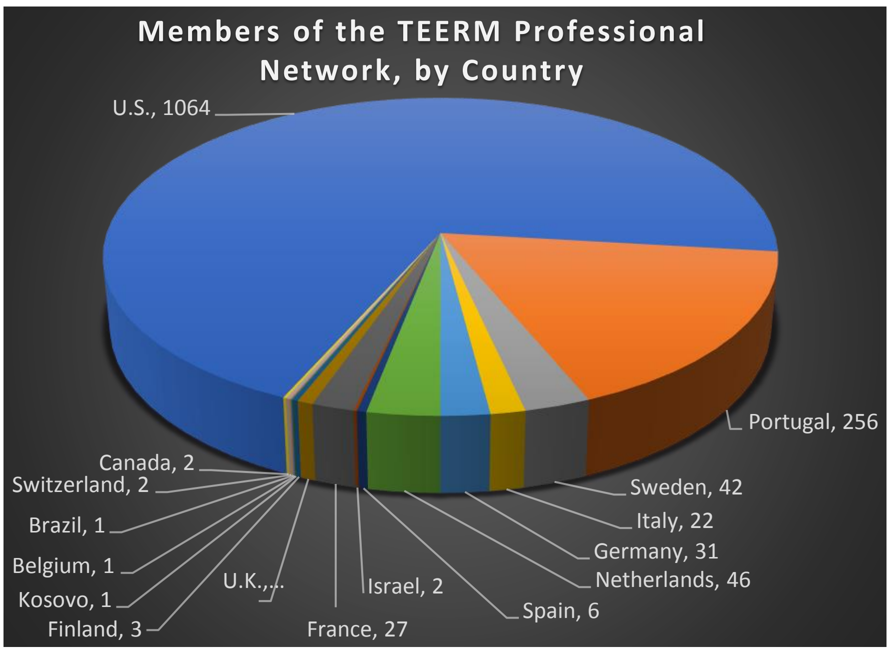


Figure 7b. *TEERM professional network – by country.*

6.2 Projects and Accomplishments

TEERM developed and implemented projects that reduced risks to the NASA mission. The following sub-sections outline some noteworthy accomplishments with benefit to the NASA mission with project specific details provided in Sections 7 and 8.

6.2.1 Waste Minimization and Hazardous Waste Treatment

- Waste minimization projects PPONAs at NASA Centers, Air Force locations, and in Portugal (Section 7.1).
- TEERM evaluated bio-based citric acid as an alternative for the more toxic nitric acid passivation in a project sponsored by NASA KSC GSDOP (section 7.1).

6.2.2. Recycling and Biodegradable Material

- TEERM initiated the first-ever demonstration at a NASA site for recycling Spent Blast Media (SBM) for use in onsite concrete construction projects. This technology is now approved by KSC for use (Section 7.3).
- TEERM leveraged information from a National Defense Center for Energy and Environment (NDCEE) Corn Hybrid Polymer (CHP) blasting project to initiate a JSC study on the technology. TEERM arranged for a technology demonstration and worked with JSC on defining technical requirements and identifying potential technology transition obstacles. The technology was validated for use by JSC (Section 7.3).

6.2.3 Corrosion Prevention and Control

- TEERM identified and evaluated replacements for coatings containing CrVI. TEERM managed collaborative studies with contributions from outside NASA EMD. From 2003 to 2013, TEERM efforts resulted in almost $2M being awarded to the NASA CTL (Section 7.4).
- TEERM received NASA approval for an innovative idea to conduct flight-testing of several CrVI-free coatings aboard a NASA P-3 aircraft at WFF. This demonstration/validation was the first field demonstration on aircraft flight equipment for the Agency. Primary among the innovative features of some of the coatings is their corrosion inhibiting makeup (Section 7.4).
- After testing isocyanate-free coatings, five systems were added to the Approved Products List (APL) of NASA-Standard (STD)-5008, *Protective Coating of Carbon Steel, Stainless Steel, and Aluminum on Launch Structures, Facilities, and Ground Support Equipment*. These coating systems were the first low-VOC coatings added to the APL giving maintenance personnel environmentally-friendly alternatives while ensuring that performance standards are met (Section 7.4).
- TEERM worked with GSDOP, CTL, WFF, WSTF and AFSPC to identify, demonstrate and validate environmentally-preferable coatings. Four coating systems passed the minimum criteria set forth in the KSC NASA-STD-5008B (Section 7.4).
- TEERM managed a large, multi-Agency collaborative effort to demonstrate/validate alternative coatings to reduce heavy metals, most notably CrVI. TEERM took the lead in developing and validating a new and improved procedure for panel preparation to

mitigate previously observed anomalies. Project recommendations included modification of NASA specifications, drawings, and drawing notes to include CrVI-free pretreatments as an option for use (Section 7.4).

- TEERM initiated an alternative coatings demonstration/validation project with ESA. One innovative aspect of this project was TEERM's identification of coatings uniquely available in Europe that offer promise for NASA and DoD applications (Section 7.4).
- TEERM developed the project concept, formulated the team, and garnered project buy-in and sponsorship from GSDOP for two alternative coatings projects (Section 7.4). One innovative aspect of these projects was the experimental designs that maximized the generation of useful data while keeping the number of test articles as low as possible.

6.2.4 Ozone Depleting Substances, Solvent Substitution, and Aqueous Cleaners

- AP2 developed a "Consumer's Guide to Alternative Parts Washers" to assist environmental managers, shop owners, and procurement personnel in deciding which environmentally-preferable parts washer will work best for their shops. Six NASA centers working together achieved nine-times the amount of work reviewing alternative cleaners than could be completed at one test site during the same time-period at no additional cost to the individual centers (Section 7.5).
- TEERM leveraged the results of the ESTCP-funded project "Portable Laser Coating Removal System" (PLCRS) to start an intensive series of field demonstrations at Glenn Research Center (GRC), Wright-Patterson Air Force Base (WPAFB), and KSC. Lasers were tested on a variety of GSE from several NASA centers and Boeing for use on several types of Orbiter hardware including tile cavity applications as well as aluminum honeycomb, Inconel, and other sensitive substrates (Section 7.5)

6.2.5 Lead in Electronics

- AP2 performed a comprehensive baseline study of the risks associated with continued use of eutectic tin-lead solder alloys for electronic soldering and performed a state of the technology assessment of lead-free alloys (Section 7.6).
- TEERM developed the project concept, formulated the team, and garnered project buy-in from various military and aerospace partners to test and evaluate the reliability of promising lead-free solder alloys. TEERM authored the project's industry-leading joint test plan, which is internationally recognized (Section 7.6).

6.2.6 Green Engineering and Energy Solutions

- TEERM initiated a wind turbine performance assessment at JSC with support from DOE and NREL (Section 8.1). This assessment was one of the first studies of its kind to ascertain the effects of roof-mounted wind turbines.
- TEERM co-managed a field demonstration of an innovative hydrogen fuel cell mobile light tower coupled with advanced energy-efficient lighting at KSC (Section 8.2).
- In a joint effort among TEERM, JSC, DOE, NREL, and two universities, TEERM formulated a demonstration/validation project to monitor green roof water storage and runoff for development of a modeling tool to be used to compare and predict green roof performance across different climates (Section 8.3).

7 Projects with Environmental Focus

TEERM and AP2 projects with an environmental focus include those related to waste minimization, treatment of HAPs, recycling, Corrosion Prevention and Control (CPC), replacement of ODSs, and lead-free electronics. Often overlaps exist between these categories (for example, the nitric acid passivation project sought to minimize waste but addressed a corrosion issue). Appendix B includes a list of all projects discussed in this report and sections where the discussion is located.

7.1 Waste Minimization and Hazardous Waste Treatment

NASA and partners have been working to develop and implement waste minimization initiatives. Waste minimization has been driven by environmental regulations and EOs, including RCRA and EO 13693. NASA operations often use hazardous materials and create waste and emissions that can be hazardous to human health and the environment. Potential impacts include human health effects, environmental impacts, non-compliance with regulations, and increased cost and liability.

Reducing hazardous waste generation must be accomplished while achieving mission requirements within constrained funding. Specific challenges include material substitution while remaining within technical specifications for equipment, and process changes and technologies that strive to reduce waste while meeting mission needs and realizing reasonable payback period.

TEERM (and AP2) worked on a number of projects with NASA stakeholders and outside partners. Projects include the early AP2 work on conducting PPONAs [also referred to as Pollution Prevention Opportunity Assessments (PPOAs)] at NASA centers, Air Force locations, and in Portugal in collaboration with C3P. TEERM also worked on projects that evaluated citric acid as an alternative to nitric acid passivation.

7.1.1 Pollution Prevention Opportunity Assessments

Pollution Prevention (P2) was the environmental policy of the U.S. as declared in the Pollution Prevention Act of 1990. The NASA AP2 Program Office identified common P2 needs that affected manufacturing, maintenance, and institutional processes. This approach aimed to encourage partnering, leverage limited resources, avoid duplication of effort, and reduce total cost of process ownership. These efforts benefited NASA systems acquisition, operation, sustainment, and maintenance processes through HazMat reduction and elimination.

7.1.1.1 Pollution Prevention Opportunity Assessments at NASA Centers

AP2 conducted PPOAs that described and analyzed manufacturing and maintenance processes at NASA centers to identify and integrate potential P2 opportunities. Initial PPOAs were completed for all 13 NASA locations, and a Senior Management Council assigned action to determine potential for cost efficiencies and reduced environmental impact liability associated with metal finishing facilities, photographic labs/facilities, and multiple large thermal vacuum chambers and acoustic test facilities within the Agency.

Bringing individual NASA centers together to address common needs helped reduce the economic strain and potential operational disruptions on individual centers to solve their waste generation issues. Implementation of identified opportunities reduced hazardous waste generation; improved resource allocation; reduced environmental, safety, and health costs; and improved worker safety.

7.1.1.2 Depainting Pollution Prevention Opportunity Assessments for Cape Canaveral Air Force Station

AP2 assessed risks and opportunities of the structures-maintenance activities at Cape Canaveral Air Force Station (CCAFS). AP2 focused on identifying and reducing risks associated with particulate matter emissions and hazardous waste while improving down-times, increasing mission readiness, and meeting applicable laws and regulations.

AP2 identified and ranked three commercially available depainting technologies (Steel-Magic®, Sponge-Jet®, and QuikTrip®-A) that appeared feasible for meeting CCAFS mission needs (Figure 8). All are abrasive blast technologies that remove coatings and provide the necessary surface profiles for recoating associated structures. The products can also be recycled many times, thus reducing wastes associated with depainting operations and in some circumstances, costs as well. Additionally, some new equipment technologies were discussed that can be used in conjunction with current or recommended depainting technologies that enhance systems environmental attributes. The recommended equipment helps limit particulate emissions, aids in recycling material, and reduces time associated with depainting processes. These findings helped the AFSPC select depainting technologies for use in a follow-on depainting demonstration at CCAFS in early 2007.

Figure 8. *Preparation of test panel using SpongeJet®.*

7.1.1.3 Pollution Prevention Opportunity Assessment in Portugal

C3P and NASA formed an Assessment Team consisting of AP2, ISQ, and INEGI to provide environmental technology need assessments at 24 government, military, and commercial manufacturing and maintenance facilities in Portugal. The objective was to evaluate industrial processes for existing HazMat and VOC uses, identify technologies or processes that could be used to meet EU and Portuguese legislative limit requirements, and determine collaborative project areas that could yield benefits to Portugal and NASA in HazMats and VOCs reduction or elimination.

The Team discovered that most sites visited were not fully prepared to meet new VOC requirements and determined that meeting the challenges of EU and Portuguese reductions in VOC emissions and HazMat uses requires a combination of economic and integrated technology efforts in best management practices, control technologies, and identification and validation of alternative materials. Other P2 opportunities were identified that led to additional NASA and

C3P joint efforts, including the demonstration and validation of alternatives to CrVI conversion coatings and primers, non-Trichloroethylene (TCE) oxygen line cleaning systems, lead-free solder, and reduction of VOCs in ink marking.

7.1.2 Alternative to Nitric Acid Passivation

NASA, DoD, and ESA have similar equipment and processes that require the passivation of stainless steel for protection against corrosion. The standard practice has been the use of nitric acid for passivation of stainless steel alloys. While nitric acid exhibits excellent performance, numerous environmental, safety, and operational issues exist associated with its use. Nitric acid used to passivate stainless steel results in a large amount of hazardous waste and Nitrogen Oxide emissions, and the process includes use of hazardous materials.

Citric acid is an alternative to nitric acid for the passivation of stainless steel. Citric acid offers various benefits including increased safety for personnel, reduced environmental impact, and reduced operational cost. While citric acid use had become more prominent in industry, there was little evidence that citric acid is a technically sound passivation agent, especially for the unique and critical applications encountered by NASA and ESA. TEERM worked with NASA centers [KSC, Stennis Space Center (SSC), WFF, WSTF], CTL, GSDOP, DoD, and ESA to evaluate citric acid as a safer alternative to nitric acid for stainless steel alloys passivation.

The testing results have shown that citric acid performs as well as, or better than, nitric acid regarding corrosion resistance (Figure 9). The citric acid passivation also does not affect adhesion of subsequently applied coatings.

Figure 9. *Test panels soaking in citric acid.*

Use of citric acid reduces the environmental, safety, health risks, and material handling and disposal costs associated with the use of nitric acid. Citric acid removes free iron from the surface while leaving behind beneficial heavy metals presenting operational benefits. Citric acid immersion baths also retain their potency longer, thus requiring less frequent refilling and reduced volume and potential toxicity of effluent and rinse water (Lewis et al., 2013a; Lewis et al., 2013b; Kessel, 2016a; Kessel, 2016b).

7.2 Treatment of Hazardous Air Pollutants

NASA operations that emit HAP emissions create a risk of occupational exposure and releases to the environment. Potential impacts associated with HAPs release include human health effects, environmental impacts, non-compliance with regulations, and increased cost and liability. Regulatory drivers include:

- CAA Title III and V
- EO 13693

Many existing air pollution control systems and materials were not designed to meet the HAP emission standards that were being adopted or considered. In addition, these older systems often suffered from poor reliability and high operations and maintenance costs because of their age or design. One of the largest contributors of HAPs is paint booths. Decreasing HAP emissions associated with NASA operations is critically important to ensure operational flexibility as well as to avoid the imposition of more stringent requirements to major sources of HAP emissions.

7.2.1 Volatile Organic Compounds Membrane Project

Technologies currently used within process lines and remediation sites to capture, destroy, or otherwise reduce VOC stack emissions include catalytic oxidizers, thermal regenerative oxidizers, carbon adsorption/solvent recovery, hybrid concentrators, and gas turbines. Recently, semi-permeable membranes have been developed that allow for separation and capture of VOCs from entrained air-streams.

A hollow fiber-based vapor permeation process employs a lumen-side feed flow essentially at atmospheric pressure and a vacuum on the shell side. The excellent separation performance obtained with small membrane modules inspired an exploration of the performances of larger commercial-size hollow fiber cartridges and multiple cartridge-containing modules for treating VOC-containing gas streams.

VOCs generated during certain industrial processes and remediation activities are a primary concern with increasing environmental regulations continuing to reduce the allowable level of VOCs that can be emitted. Rubbery membranes, namely silicone membranes, can selectively capture VOCs. This characteristic has been used effectively to recover VOCs from air streams in past specific processes; however, the systems were bulky and not as efficient as newly developed VOC-capturing membranes.

TEERM teamed with the New Jersey Institute of Technology (NJIT), Applied Membrane Technology, and Chembrane Inc., to test a novel type of membrane that filters and captures VOCs from contaminated process air streams. The technology can lower VOC emissions by more than 95%. Captured and condensed emissions can then be reused or recycled (fuel/blending). Several processes at NASA and DoD were identified as demonstration sites; these sites include a groundwater remediation site, painting/coating facility, fuel-tank farm, several precision cleaning facilities, and some onsite laboratories. TEERM also conducted a review and assessment of the Railway Equipment Maintenance Company (EMEF) industrial plant in Lisbon, Portugal. EMEF repairs and maintains more than 75% of the railway equipment in Portugal and is a viable candidate for demonstration of the VOC membrane technology outside the U.S.

TEERM began testing the membrane technology in 2007. The pilot studies focused on emissions from a batch reactor in a pharmaceutical plant (emitting 2.5% toluene, 4% ethyl acetate, and 14% methanol at a rate of 10–80 l/m) and air emissions from a paint booth (emitting very low levels of VOCs in the 5 – 100 pump range).

Field testing was accomplished at NASA's WFF on entrained VOCs emitted from an old fuel and chemical dumping location near the airfield that had been undergoing approved technologies and procedures to remediate the site. TEERM and Chembrane Inc., personnel set up the equipment and witnessed entrainment and capture of the identified VOCs during the performance period. The assessment successfully proved the technology functioned as advertised and closely mirrored results from previous laboratory test results.

7.3 Recycling and Biodegradable Materials

Current methods for performing maintenance and refurbishment of coating on metal substrates often involve labor intensive techniques (e.g., sanding, bead-blasting, etc.), sometimes coupled with HazMat application beforehand to loosen the coating, or afterwards to clean the substrate. This process can result in safety or occupational health risks to workers, as well as damage to the underlying substrate. Additionally, exposure concerns typically do not end once the product has reached its usefulness end. This is especially true in cases where the spent material is either disposed of into a landfill or burned. These disposal methods present inherent risks because of the potential for run-off situations and ashes floating off into an uncontrolled area.

Regulatory drivers for this risk include:

- EO 12196 (Occupational Safety and Health Programs for Federal Employees0
- 29 CFR 1960 (OSHA Standards)
- NASA Strategic Sustainability Performance Plan
- EO 13693
- REACH

One of KSC's largest waste-streams is hazardous and non-hazardous SBM. Various types of blast media (steel, pumice, plastic, etc.) are used for different situations that call for coatings and paints removal. Additionally, for processes including non-destructive evaluation and inspection of weld-lines, stress-crack identification, substrate failure analysis and inspections, as well as periodic removal of coatings, specific types of SBM were recycled, but still were using petroleum-based products, and often involved hazardous post-use processes involving wash, or wipe-down chemicals such as Methyl Ethyl Ketone (MEK).

KSC asked TEERM to identify methods other than landfill disposal for its SBM. TEERM identified several best management practices. One practice involved the SBM inclusion into useable end-products such as tables, chairs, parking bumpers, etc. Another practice involved using specific (non-hazardous) SBM as an alternative to virgin sand in concrete applications, and finally, a bio-based alternative to currently used plastic blast media used on delicate substrates such as aluminum and other alloys, for example, types used on the Shuttle Solid Rocket Boosters (SRBs). After NASA review, a determination was made that the project limit its focus to strictly non-hazardous SBM. Also decided was that the liability to NASA was too high to consider inclusion into end-products such as tables, chairs, etc., so NASA TEERM instead proceeded to develop projects to validate and demonstrate a bio-based alternative to plastic blast media, and to use non-hazardous spent abrasive blast as an alternative aggregate in concrete applications.

7.3.1 Evaluation of Non-Hazardous Spent Blast Media in Concrete Applications

Historically, one of NASA's largest waste streams is combined (hazardous and non-hazardous) SBM generated from various abrasive blasting processes such as corrosion control, inspection procedures, and coating removal, among others. Various branches of the DoD have led successful pilot-projects using non-hazardous SBM as an alternative aggregate to virgin sand in various concrete mixtures.

Benefits for use of non-hazardous SBM as an alternative aggregate in concrete mixes include:

- Reduces or eliminates the amount of disposed-of non-hazardous SBM, positively impacting a historically large waste-stream.
- Reduces run-off chances, or blow-off situations whereby the SBM can affect worker's safety, as well as the surrounding environment.
- Reduces disposal costs, as well as the cost of using SBM rather than virgin sand.
- Reduces carbon footprint.
- Supports KSC Sustainability Plan.

TEERM helped NASA evaluate the applicability of reducing the amount of non-hazardous SBM currently disposed of as solid waste, by incorporating non-hazardous SBM as an alternative aggregate in various concrete projects. This project was conducted from 2012 to 2014. Project partners included KSC, Hansen Slag Cement, and United States Air Force (USAF) CCAFS/Patrick Air Force Base (PAFB).

KSC's Construction of Facilities (CoF) Office contracted the construction of two small concrete structures incorporating the modified concrete mixture and observed how it performed as a comparison to traditional concrete.

Onsite and laboratory test results, as well as subsequent interviews with installation technicians and KSC personnel, indicate the alternative concrete met all stated requirements for the specific locations and was generally the same to transport, handle, work with, and apply.

The results and recommendations have been shared across the Agency and the project is considered a model for potential future efforts across NASA. As a result of TEERM's collaborative efforts, KSC has referenced the spent media recycling process in its Center-Wide Sustainability Plan and updated contracting language to require consideration of using non-hazardous SBM in future applicable KSC concrete work.

7.3.2 Evaluation of Corn-Based Alternatives to Plastic Blasting Media for Aerospace Applications

Maintenance and corrosion protection represent significant costs within supported systems life cycle. Many traditional methods of coating removal involve using HazMats or employ processes that have the potential to damage delicate substrate materials. Bio-based products, such as corn-based blasting media, can help NASA meet petroleum-use-reduction goals, are biodegradable, and classified as non-hazardous waste, resulting in a significant reduction in overall Agency risk.

A previous JG-PP-supported effort was the CHP Coating Removal on Delicate Substrates Project. An evaluation of the corn-based blasting media was conducted on a U.S. Navy surface ship radome sections and a passive countermeasure system. Results indicated that this media type provided an acceptable stripping rate without damaging the delicate surface. In addition, cost analyses completed for several different applications indicate significant potential cost savings upon implementation, mostly attributed to the use of water for wash-down and wipe-down post processes rather than chemicals (MEK, etc.).

The technology was added to a military specification for corrosion control after the Departments of Defense and Homeland Security conducted separate tests and subsequently approved eStrip™ GPX Type VII media (a CHP-based product) as a satisfactory alternative to certain plastic blast media types for specific applications.

TEERM arranged for demonstrations to introduce the technology to potential users at KSC and JSC. Demonstration of the Type VII media occurred in Texas at JSC's El Paso Forward Operating Location (EPFOL). Based on the demonstration, facility technicians and JSC's Engineering Team approved Type VII as an alternative blast media for use on specific components of NASA's T-38 aircraft (Griffin, 2009).

Equipment upgrades and technician training was begun at EPFOL. The use of the CHP media for specific de-coating processes will commence once a need is identified, and funding is allocated to support subsequent NASA testing and evaluation activities. This activity will be the first NASA process known to use this bio-based technology. Other applications were explored, but not further pursued.

7.4 Corrosion Prevention and Control

CPC provides a functional benefit to NASA equipment and limits maintenance costs. Many CPC technologies, however, use materials and processes that are regulated by environmental, safety, and health rules. NASA cost reduction strategies seek to minimize environmental health and safety concerns and reduce total maintenance costs. Concerning CPC, key issues include: 1) provide long-term corrosion control benefits; 2) minimize environmental, health and safety impacts of CPC materials and processes; 3) prioritize opportunities based on projected impacts; 4) implement within existing maintenance strategies, logistical constraints, and physical plant capabilities; and 5) improve training for sustainment personnel. Each of these challenges is interrelated, which further complicates the process.

NASA also has an ongoing need to maintain equipment in accordance with technical specifications while also meeting environmental requirements. Maintenance at KSC is governed by NASA-STD-5008B (*Protective Coating of Carbon Steel, Stainless Steel, and Aluminum on Launch Structures, Facilities, and Ground Support Equipment*) that establishes practices for the protective coating of launch facilities used by or for NASA programs and projects. NASA-STD-5008B includes a list of coatings that have previously been tested and qualified. The list, however, includes coatings that have very high VOC levels that are no longer compatible with stringent environmental regulations in certain states and municipal regions. The limited number of approved coatings in NASA-STD-5008B leads to the risk of material obsolescence.

NASA- STD-5008B also calls for the use of inorganic zinc primers. Zinc has a long history of proven corrosion resistance for structural steel. Zinc, however, has come under increased scrutiny because of concerns about zinc leaching into the environment surrounding the launch pads. Zinc-free coatings systems are therefore also of interest. Regulatory drivers include:

- NESHAP
- RCRA
- 29 Code of Federal Regulations (CFR) 1960
- NASA Strategic Sustainability Performance Plan
- REACH

7.4.1 Hexavalent Chromium-Free Coatings Projects

A common coating system for aerospace applications on aluminum substrates consists of a chromated conversion coating, a primer (typically chromated) and a topcoat. Chromated conversion coatings and primers offer excellent corrosion protection and adhesion characteristics. CrVI is a known carcinogen, however, and is being regulated heavily in the U.S. and EU. The identification of replacements for chromium containing coatings that offer similar corrosion protection is very important to the aerospace industry. Also, paints that contain high VOCs levels are being regulated and are hazardous to the environment and to human health.

7.4.1.1 Early Supported Efforts in Hexavalent Chromium-Free Coatings

TEERM efforts in alternative coatings/surface preparation processes began in the first program year when TEERM engineers served as NASA liaison to the DoD JG-PP. Three active JG-PP coatings projects at the time were the “Non-Chrome Primers for Aircraft Exteriors” project, the “Low/No VOC and Nonchromate Coatings for Support Equipment” project, and the “Nonchrome Aluminum Pretreatments” project. TEERM’s role in these projects—as it would be for many joint projects to follow—was to ensure the test and evaluation program would provide meaningful results to NASA. To that end, TEERM ensured that the project’s test plan incorporated NASA’s critical technical and performance requirements and alternative coatings of interest to the Agency. TEERM also secured the support of NASA corrosion SMEs and Shuttle materials and process engineers at critical points in the project.

In the case of the “Low/No VOC and Non-Chromate Coatings for Support Equipment” project, TEERM helped facilitate and oversee lab testing and atmospheric (beach exposure) testing of select coatings at KSC and field testing of the coatings on GSE at CCAFS and PAFB. TEERM disseminated the findings from these studies throughout NASA centers and the Shuttle Program.

The most prominent outcome of these early leveraged studies related to follow-on efforts that NASA initiated towards the end of the "Non-Chrome Primers for Aircraft Exteriors" project (ESTCP/JG-PP; 1995–2003). NASA and Boeing–Palmdale (Space Shuttle Orbiter Project) decided to flight test one of the promising non-chrome primers on the flipper doors of the Columbia Orbiter prior to STS-93 (Figure 10). TEERM supported Boeing in testing, inspecting, and photographing the flipper doors on Columbia while Columbia was in the Orbiter Processing Facility being prepared for launch in 2001. The results of the flight testing revealed that the non-chrome primer performed as well as the chromate-based control during Shuttle launch and re-entry. Following the successful testing, Boeing ultimately elected to apply the non-chromate primer to some brackets in the Orbiter's Payload Bay.

In the case of the ESTCP/JG-PP "Non-chromate Aluminum Pretreatments" project, NASA leveraged the project's results to ultimately implement a non-chromate coating system for use on the aluminum alloy SSP SRBs. The SRB Project conducted a project to identify and qualify alternatives for the traditional, qualified chromate coating system and pretreatment. This project gathered information on corrosion protection, bond strength, and other critical performance criteria unique to NASA. Two pretreatments and two coating systems met the SRB Project criteria and were recommended. NASA implemented a chromium-free primer-pretreatment system in June 2002. This change affected all structural aluminum parts of the SRBs. The first hardware flew in fall 2002.

At the time of these JG-PP chromium alternative projects in the late 1990s and early 2000s, the SSP had only provided limited funding towards finding replacements for CrVI in primers and conversion coatings, and Shuttle contractors were not well tied in to what the DoD was doing in chromium replacement. TEERM's involvement in these projects and active participation in multiple agency working groups allowed important data and conclusions from these chromium coatings projects to be efficiently disseminated within the Agency. As a result, NASA engineers could come up to speed quickly on the chrome issue, and the Shuttle program avoided $50,000 in testing costs by using JG-PP's nonchrome primer test data.

7.4.1.2 Later Efforts in Hexavalent Chromium-Free Coatings

C3P worked with AP2 to launch the "Alternatives to High-VOC Chrome Coatings" project in 2004. The focus of this test and evaluation effort was chrome-free, low-VOC conversion coating alternatives to Alodine 1200 for use on common aluminum airframe alloys. TAP Portugal and OGMA also participated in this project. This effort represented AP2/TEERM's first international coatings project and the second TEERM project to involve testing on flight hardware.

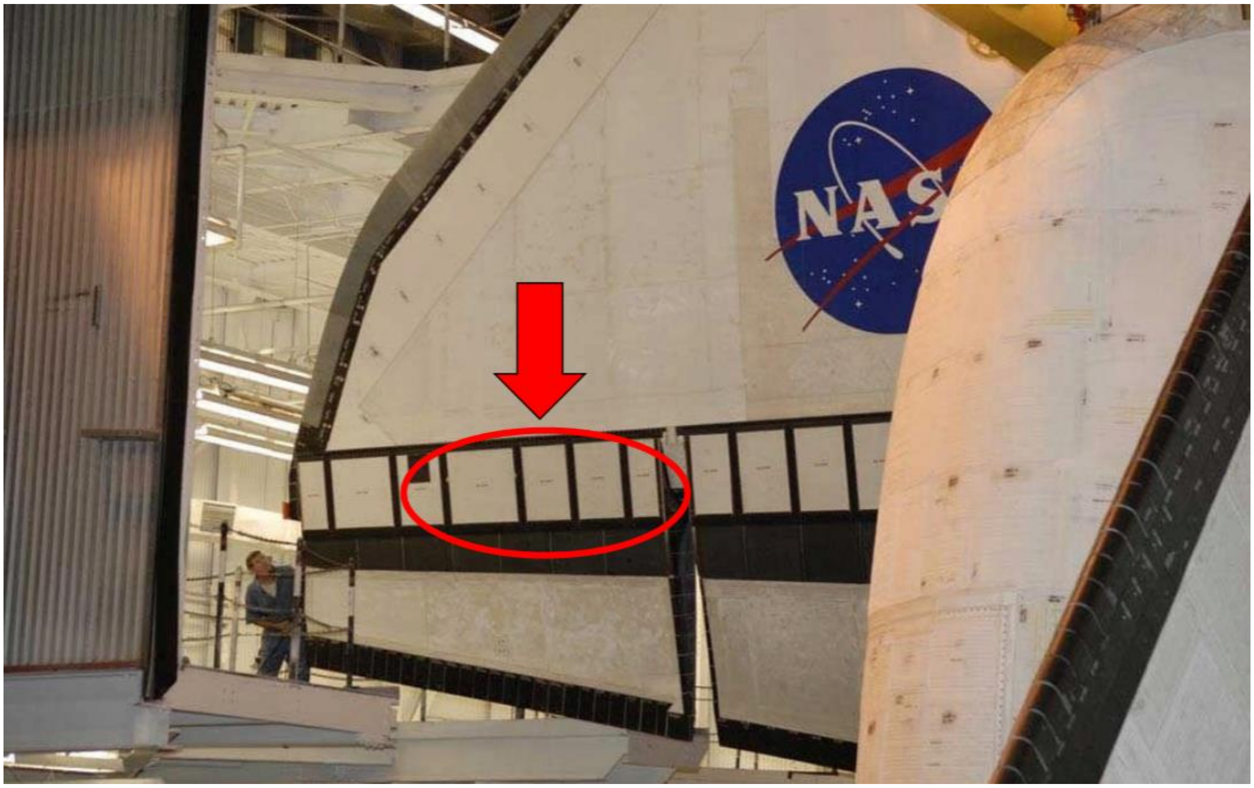


Figure 10. *Flipper doors on Orbiter Columbia where chrome-free primer was applied as part of the ESTCP/JG-PP Non-Chrome Primers for Aircraft Exteriors Project.*

Two coating systems that consisted of non-chromate pretreatments and low-VOC coatings were applied to the exterior of an Airbus A319 aircraft door for flight testing in November 2004. Test panels were also prepared for a series of laboratory tests in Portugal and at KSC. Follow-up assessments on the aircraft door condition showed that both painting systems were in excellent condition years after painting, showing no signs of peeling or observable defects.

Beginning in 2005, TEERM began developing and leading its own alternative coatings projects in part because of JG-PP's move away from leading projects to supporting them. The first such TEERM-led coatings project, "Non-Chrome Coating Systems for Aerospace," was also the first in a series of TEERM coatings projects to examine entire coating systems (pretreatment, primer, and topcoat) that contain little or no chrome. This project was a coordinated effort by NASA and the USAF. Stakeholders included personnel from KSC, MSFC, Air Force Research Laboratory (AFRL), Hill Air Force Base, Boeing, ATK Thiokol, and USA. This project analyzed the corrosion protection properties of several chrome-free systems to determine whether other viable alternatives should be further tested.

TEERM developed and led several more CrVI-free coatings projects focused on applications such as GSE and launch facilities between 2008 and 2017. Table 4 shows the scope and objectives of these as well as all TEERM alternative coatings projects. These coatings projects differed from each other either by the application, tests performed, alloys, or coatings tested. The test plans and test reports contain details on each study.

One of the more recent projects of note was a collaborative coatings study between NASA and ESA titled "NASA/ESA Verification of Hexavalent Chromium-Free Coatings." In 2009, TEERM spearheaded the establishment of an agreement between NASA and ESA to cooperate on materials replacement efforts, with hexavalent chrome-free coatings being the top priority. This priority was in part because of Europe's focus on reducing CrVI use in manufactured goods by way of the REACH Directive. While the aerospace industry was exempt from REACH at the time, uncertainty existed if and how long that exemption would last. Since both NASA and ESA use CrVI coatings on flight hardware and ground systems, collaboration made sense to share resources and expertise.

TEERM took the lead on developing the project in close coordination with materials engineers from the ESTEC located in Noordwijk, the Netherlands. TEERM also engaged project participation from the NASA CTL. As of this writing, the first phase of this NASA-ESA hex chrome testing is complete and second phase of testing has begun. Coating alternatives, alloys, test methods, and test locations were selected to maximize the project value and efficiencies. For example, test coupon alloys were selected by NASA and ESA based on common alloys used across both agencies. NASA conducted those tests critical for NASA, and ESA conducted tests they deemed critical.

Part of the success of the "NASA/ESA Hexavalent Chromium-Free Coatings" project was the ability to leverage results and conclusions from three prior TEERM coatings studies: "The Hexavalent Chrome Alternatives for Aerospace" project (2012); the "Hexavalent Chrome-Free Coatings for Electronics" project (2013); and the "Evaluation and Transition of Non-Chromated Primers" project (2016). This capability increased the likelihood that the alternatives being tested would pass.

Table 4. *CrVI projects facilitated, managed, or significantly enhanced by TEERM.*

Project	Application and NASA HazMats of Interest	Project Objective	Project Distinguishing Features	Status	Final Reports and Other References
Non-Chrome Primers for Aircraft Exteriors (JG-PP) (1995–2003)	Aircraft exteriors and moldlines HazMats: Alodine 1200 (pretreat) and Koropon (primer)	Qualify environmentally acceptable alternatives for chromate-containing primers used on military aircraft exterior mold line skins at the Boeing Company Military Aircraft and Missiles Systems Group facility in St. Louis, MO.	• NASA contractor Boeing used data from this project to gain approval to apply the most promising CrVI-free primer to the Orbiter Columbia flipper doors, which then underwent spaceflight testing.	Project completed	Kessel, K. and M. Rothgeb, 2011. *NASA TEERM Hexavalent Chrome Alternatives Projects.* NASA, KSC, FL. KSC-2011-017.
Low/No VOC and Nonchrome Coatings for Support Equipment (JG-PP) (1999–2003)	Exterior surfaces of mobile and fixed, combat- and aviation-related ground equipment in powered and non-powered categories.	Conduct laboratory and field testing of alternatives to conventional primers and topcoats used for coating support equipment at DoD and NASA facilities with emphasis on coatings that reduce or eliminate CrVI, lead, VOCs, and HAPs.	• NASA donated use of a generator cart, located at CCAFS, as a test article. • NASA KSC also conducted heat soak and beach atmospheric testing. • NASA also specified two zinc primers be tested.	Project completed	JG-PP, 2001. "Joint Group on Pollution Prevention". Accessed 9/25/17 at: http://infohouse.p2ric.org/ref/20/19926/JG_PP/jg_pp.pdf.
Nonchrome Aluminum Pretreatments (ESTCP and JG-PP) (2000–2006)	Pretreatment of aluminum alloys and post-treatment Ion Vapor Deposited (IVD) aluminum and anodized aluminum alloys HazMats: Alodine 1200 (pretreat), Deft 44-GN-7 (primer), and Deft 03-W-127A (topcoat)	Demonstrate and validate the performance of non-CrVI aluminum pretreatments on broad range of DoD and NASA equipment. Specific to NASA, this project would provide needed data from salt fog testing of Alodine 5200/5700, a potential replacement for Alodine 1200 that USA-SRB had recently tested.	• USA prepared aluminum test panels with chromium-free conversion coating as in-kind contribution to the project. • USA used data from the project to help qualify and implement chromium-free primer-pretreatment system for use on aluminum alloy SRBs. • TEERM used project's test data to assist NASA centers in meeting recommendations set forth by SMC Action Item J-1.	Project completed	ESTCP, 2003. *Non-Chromate Aluminum Pretreatments, Phase II Interim Report*, Project #PP0025, Environmental Security Technology Certification Program, August 2003. Accessed 8/27/17 at http://www.iaindy.com/Documents/ncapi.pdf.

Project	Application and NASA HazMats of Interest	Project Objective	Project Distinguishing Features	Status	Final Reports and Other References
Alternatives to High-VOC Chrome Coatings for Aircraft Exteriors (C3P) (2004–2007)	Aircraft and aerospace exterior and interior surfaces HazMats: Alodine 1200 (pretreat)	C3P-led project to test in laboratory and field the chrome-free low VOC coating systems in aircraft painting operations at TAP Portugal and OGMA.	• TEERM's first international chrome-free coatings collaborative testing project. • Incorporated operational flight testing of two alternative coating systems on service door aboard TAP Airbus A319 commercial aircraft.	Project completed	Kessel, K. and M. Rothgeb, 2011. *NASA TEERM Hexavalent Chrome Alternatives Projects.* NASA, KSC, FL. KSC-2011-017. Data incorporated into final report for TEERM "Non-Chrome Coating Systems for Aerospace" Project.
Non-Chrome Coating Systems for Aerospace (2005–2009)	Aerospace HazMats: Alodine 1200 (pretreat), Deft 02-Y-40 (primer), and Deft 03-GY-321 (topcoat)	Identify and qualify entire coating systems (pretreatment, primer, topcoat) that contain little or no chrome.	• Leveraged interim findings from preceding TEERM Alternatives to High-VOC Chrome Coatings project.	Project completed	Kessel, K. and M. Rothgeb, 2011. *NASA TEERM Hexavalent Chrome Alternatives Projects.* NASA, KSC, FL. KSC-2011-017.
Evaluation and Transition of Non-Chromated Primers (w/ ESTCP; Navy-led) (2011–2016)	Aircraft exterior surfaces HazMats: CrVI-containing primers	Field demonstrate/validate CrVI-free coatings products tested in laboratory under accelerated test conditions.	• Unique test platform (operational NASA and DoD aircraft) make this project different from other TEERM chrome-free projects. • Also included some newer products qualified to MIL-PRF-23377 Class N and MIL-PRF-85582 Class N.	Project completed	Kessel, K. and M. Rothgeb, 2011. *NASA TEERM Hexavalent Chrome Alternatives Projects.* NASA, KSC, FL. KSC-2011-017.
Hexavalent Chrome-Free Coating Systems for Aerospace (2008–2012)	Aerospace HazMats: Alodine 1200 (pretreat), Deft 02-Y-40 (primer), and Deft 03-GY-321 (topcoat)	Identify and qualify several new coating products.	• Leveraged findings from preceding TEERM: Non-Chrome Coating Systems for Aerospace project. • Included additional performance requirements and test procedures • NASA's CxP contributed some coatings to be tested.	Project completed	

Project	Application and NASA HazMats of Interest	Project Objective	Project Distinguishing Features	Status	Final Reports and Other References
Hexavalent Chrome-Free Coatings for Electronics (2010–2013)	Electronics for aerospace and ground HazMats: Iridite 14-2 (pretreat) and Alodine 1200 (pretreat)	Test hexavalent chrome-free coatings for use on military and aerospace electronics housings, fixtures, chassis, and attachments. Testing encompassed coatings ability to resist corrosion as well as determine EMI/Radio Frequency Interference (RFI) properties.	• Test article design and test procedures were different from those in other TEERM chrome-free projects. • Incorporated corrosion testing at KSC beach site and launch site. • Coating materials will be some of the same ones tested in other TEERM chrome-free projects to allow for comparison.	Project completed	Kessel, K, 2012a. Hexavalent Chrome Free Coatings for Electronics Applications: Joint Test Report. NASA, KSC, FL. KSC-2012-263. Rothgeb, M. and K. Kessel, 2013. Hexavalent Chrome Free Coatings for Electronics Applications: Joint Test Report NASA, KSC, FL. KSC-2013-111.
NASA/ESA Verification of CrVI-Free Coatings (2011–2018) (estimate)	Aerospace (rockets and spacecraft) HazMats: CrVI containing pretreatments/ primers	Test and qualify both "old" and "new" chrome-free conversion coatings and primers of interest to both NASA and ESA as part of a coating system.	• Leveraged findings from: "Hexavalent Chrome Alternatives for Aerospace" (2012); "Hexavalent Chrome Free Coatings for Electronics Applications" (2013); and "Non-Chromated Primers" (2016). • Due in part to the intended application (coating systems for NASA and ESA), the coating materials tested, and some of the ESA tests in this project are different from those being employed in other TEERM chrome-free projects.	Some testing complete and documented by TEERM in 2017. Other testing is ongoing outside of TEERM (by ESA at Kourou and KSC)	Rothgeb, M. and Kessel, K., 2015. NASA and ESA Collaboration on Hexavalent Chrome Alternatives – Pretreatments with Primers Screening Final Test Report. National Aeronautics and Space Administration, Kennedy Space Center, FL., Document ID: 2015014973. Kessel, K., 2015. NASA and ESA Collaboration on Hexavalent Chrome Alternatives Pretreatments Only Interim Test Report. National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-E-DAA-TN25897.

Project	Application and NASA HazMats of Interest	Project Objective	Project Distinguishing Features	Status	Final Reports and Other References
Hexavalent Chrome Alternatives Ground Systems Development and Operations (w/ GSDOP) (2012–2015)	GSE and Electrical Ground Support Equipment (EGSE) HazMats: CrVI-containing pretreatments/ primers	Evaluate and test non-chromated coating systems (pretreatment, primer, and topcoat) as replacements for hexavalent chrome coatings currently used on GSE and EGSE.	• Tested alternatives of interest to ESA, e.g., currently not targeted by RoHS / REACH. • Raytheon conducted surface resistivity testing as in-kind.	Project completed	Some requirements rolled into "NASA-ESA Hex Chrome Alternatives" effort.
Evaluation for Alternatives to Hexavalent Chromium Sealants (2012-2015)	High-temperature defense and space systems requiring sealing HazMats: hexavalent chromium-containing polysulfide sealants	Conduct screening level testing to generate the performance data to either: 1) justify the use of DFARS-compliant alternatives to hexavalent chromium sealants; 2) support a request for a DFARs exemption on an application by application basis; or 3) provide information to make decisions regarding further testing requirements for DFARS compliance.	• Project required the team to develop a new, non-standard test vehicle configuration to simultaneously evaluate sealant applications, providing sufficient and differentiable criteria for evaluating chromate and chrome-free materials in field applications. • NASA provided technical expertise on the test vehicle design, and donated time and space at the KSC beachside corrosion site for atmospheric exposure testing.	Project completed	Morose, G. *et.al.* 2013. "Evaluation for Alternatives to Hexavalent Chromium Sealants". *Metal Finishing*. Vol 111, Issue 3, pp.32-37, 63.

Project	Application and NASA HazMats of Interest	Project Objective	Project Distinguishing Features	Status	Final Reports and Other References
NASA and ESA Collaboration on Environmentally-preferable Coatings for Launch Facilities Project (2015–2018) (estimate)	Zone 4 (ambient). Of launch facilities and GSE HazMats: coatings containing CrVI, isocyanates, and zinc, or high in VOCs and HAPS	Produce and implement a JTP to generate data necessary to provide data to justify including a greater number of viable environmentally-friendly coating materials in the APL for NASA-STD-5008.	• Leveraged findings from preceding TEERM "Environmentally Preferable Launch Coatings for Ground Systems" project. • With ESA as partner, this project differs from previous GSDOP project by way of more and different coating materials and tests that ESA designated.	Short-duration and interim test results documented by TEERM in 2017. Other testing ongoing outside of TEERM (at KSC beach corrosion site, ESA ESTEC, and Kourou).	
Alternatives to Hexavalent Chromium-containing BR-127 Bond Primer (2014-2017)	Bonding of aerospace parts HazMats: BR-127 (hexavalent chromium-containing primer)	Produce and implement a JTP to provide data necessary to justify use of Defense Federal Acquisition Regulation Supplement (DFARS)-compliant CrVI-free bond primers for aerospace applications. Within NASA, objective is to mitigate the obsolescence risk with there being only one supplier of qualified chromate (BR-127) bond primer for rockets and NASA aircraft.	• The application (aerospace bond primer), coating materials, test article design, and test procedures are different from those in other TEERM chrome-free projects. Importantly to partner ESA, none of the alternatives are currently targeted by RoHS / REACH. • NASA performed corrosion resistance testing on bond primer only panels.	Phase I testing complete Q1 2017. Phase II testing is under consideration by non-NASA stakeholders, and may include examination of different tests, different processing parameters, and different adhesives.	Lamb, D., 2016. NASA TEERM Cr6+ Free Bond Primer Replacement Project. ASETS Defense 2016 Workshop. Accessed 8/27/17 at https://serdp-estcp.org/content/download/41315/394519/version/1/file/3.10-Lamb_ASETS+Defense+Bond+Primer+NASA+TEERM+Lamb+Final.pdf DeFranco, K. *et.al.*, August 1, 2017. Evaluation of Hexavalent Chromium Free Bond Primers for Aerospace and Defense Applications. *Products Finishing*. Accessed 8/217 at http://www.pfonline.com/articles/evaluation-of-hexavalent-chromium-free-bond-primers-for-aerospace-and-defense-applications

7.4.2 Environmentally-Preferable Coatings for Launch Facilities

In late 2011, TEERM received approval and funding from the NASA GSDOP to establish a project to identify and qualify environmentally-preferable coatings for ambient zone of launch pads. “Environmentally-preferable” was defined as meeting local VOC regulatory requirements and not containing isocyanates; zinc; or heavy metals, such as lead, chromium, or cadmium.

In keeping with TEERM’s desire for partnering on projects, TEERM secured commitments from ESA to provide technical and engineering support in the form of significant input and acceptance of the project’s test plan and test report. In addition, ESA decided to perform parallel atmospheric exposure testing near their launch site in Kourou, French Guiana.

Because TEERM and ESA had already begun planning for this project in 2009, testing could begin relatively soon after award by GSDOP. The project JTP was completed in December 2011, the PAR completed in February 2012, and the first of three staggered sets of coatings testing began in June 2012, with test panels comprised of ten coating systems being placed at the KSC Beachside Atmospheric Test Facility. By February 2015, some testing was complete while other tests were still in progress.

In spring 2015, with no further GSDOP funding for the effort, NASA EMD stepped in to fund the project continuation. Importantly, new scope was also added for TEERM to conduct operational environment testing of selected environmentally-preferable coatings at WFF, looking at Zones 1, 2 and 3 [(Figure 11), (Zone 1 = direct exposure SRB engine exhaust; Zone 2 = elevated temperature and acid deposition from SRB exhaust; Zone 3 = ambient temperature acid deposition exposure)].

Figure 11. *PAD 0A, location of field testing of environmentally preferable coatings at NASA WFF, photographed June 29, 2016.*

The purpose of this field testing was to assess the coatings performance in a true operational environment incorporating exposure to rocket exhaust extreme conditions. TEERM also collected corrosion rate data from WFF to compare the Wallops site corrosiveness to the KSC atmospheric exposure site

With testing still ongoing but the TEERM program ending, TEERM prepared an interim test report of the results to date from the beach site testing and launch site testing. These data indicate that more than one of the environmentally-preferable coatings and coating systems being tested on the Wallops launch pad meet NASA requirements for corrosion protection when there is no direct impingement. Where there is direct impingement, all coatings show varying signs of coating erosion, breakdown, removal, damage, or discoloration.

In this project, TEERM was successful in leveraging information from previous TEERM/AFSPC projects. TEERM also added benefit by leveraging the data from the GSDOP-funded portion of this effort into an expanded effort looking at corrosion protection for launch facilities.

7.4.3 Gas Dynamic Spray Technology Demonstration

NASA and USAF space launch facilities and support equipment are coated with materials to protect them from the harsh effects of corrosion and thermal ablation. The most commonly used coatings contain zinc, VOCs, and isocyanates. These materials, however, are subject to increasing environmental and safety regulations and concerns. To address these compliance concerns, AFSPC and NASA approved the use of Thermal Spray Coatings (TSCs). TSCs are extremely durable and environmentally-friendly alternatives but use large cumbersome equipment for application. Other concerns include difficulties coating complex geometries and the cost of equipment, training, and materials.

TEERM worked with the AF 45th Space Wing, KSC CTL, KSC, and AFSPC to evaluate a Gas Dynamic Spray (GDS) technology (commonly known as Cold Spray) as a smaller, more maneuverable repair method. The technology can result in reduced maintenance and HazMats/wastes.

This effort primary objective was to demonstrate and gain approval of GDS technology as a repair method for TSCs at AFSPC and NASA installations. AFSPC and the AF 45th Space Wing provided direct and in-kind contributions to the project. In the demonstration project, test panels showed few signs of corrosion after 18 months of exposure at the KSC Corrosion Beach Test Site (Lewis, 2008b, Lewis, 2011a).

7.4.4 Alternatives to Aliphatic Isocyanate Urethanes for Structural Steel

NASA and AFSPC commonly used paints containing aliphatic isocyanates on structural and non-structural elements. Isocyanates are toxic and these painting operations are regulated under rules promulgated by OSHA. NASA and AFSPC were interested in identifying alternative coatings that do not contain isocyanates yet meet performance requirements.

TEERM partnered with KSC, SSC, and AFSPC as part of a JG-PP project to demonstrate and validate alternatives to isocyanate polyurethanes for protecting infrastructure and support equipment. The objective was to validate alternatives to aliphatic isocyanate urethane coatings for structural steel and to qualify isocyanate-free, low VOC alternatives to be added to the NASA-STD-5008 APL. Coatings with isocyanates are completely banned from use at SSC and are strictly controlled at KSC.

Eight alternatives and two control coating systems were identified for testing. TEERM worked with NASA CTL to ensure that alternatives were tested to the requirements of NASA-STD-5008.

Phase II testing of alternatives that passed the Phase I (screening) was completed in late 2006. All the alternatives were placed at the KSC Corrosion Test Bed for 18-month marine exposure. Coatings were also applied to an engine test stand at SSC for field evaluation and inspected at 6 and 12 months (Figure 12). One system performed better than the control coatings; two systems performed similarly to the control coatings; and the other systems showed mixed results.

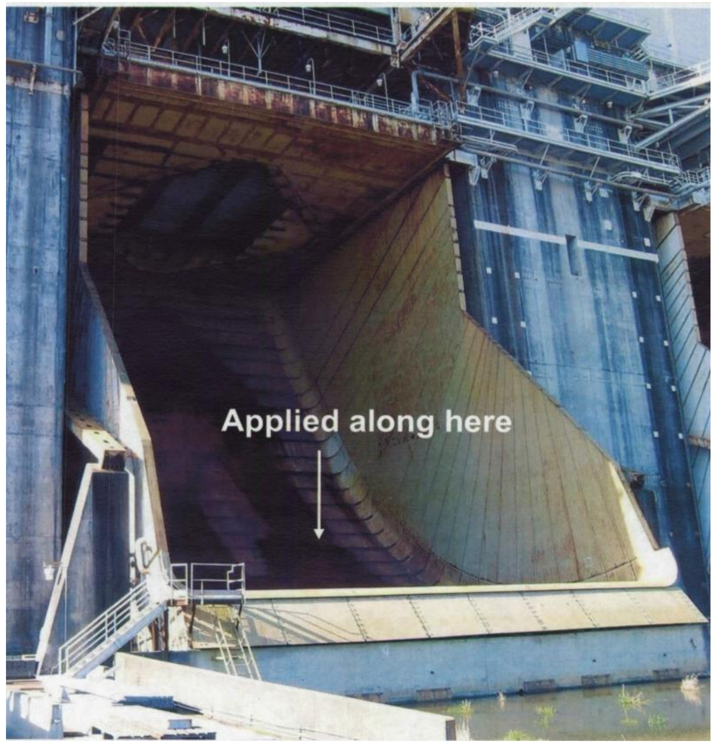


Figure 12. *Coatings were applied to an engine test stand at SSC.*

This project led to five isocyanate-free, low-VOC coating systems being added to the NASA-STD-5008B APL (Lewis 2007b, 2007c). During the recent revision, a category for low VOC coatings was added and almost all the coatings listed in that section were qualified during this or follow-on TEERM projects, such as the “Low VOC Coatings and Depainting Field Testing” project.

This project demonstrates the importance of partnerships and included stakeholders from KSC, SSC, and AFSPC directly involved in planning and execution. This project was also considered a JG-PP project and the data was shared with the JG-PP community.

7.4.5 Low Volatile Organic Compound Coatings and Depainting Project

Launch pads are exposed to extremely corrosive ambient and operational conditions. Throughout the years, TEERM has managed or supported multiple NASA efforts to test and qualify effective, low-VOC, environmentally-friendly coatings for launch structures.

Environmentally-friendly coatings have been developed to meet federal and state regulations on the amount of VOCs an installation can emit. While these coatings meet environmental requirements, they must be validated to AFSPC and NASA stringent performance requirements.

AFSPC and NASA also use abrasive blasting for depainting and/or surface preparation of structural steel that creates fine, airborne dust. OSHA regulates such operations.

The "Low-VOC Coatings and Depainting" project, which ran from 2006 to 2009, was a continuation of various AFSPC and NASA work including:

- "CCAFS Depainting and Surface Preparation Pollution Prevention Opportunity Assessment"
- "Low Emission Depainting on Steel"
- "Isocyanate Urethane Replacements on Structural Steel"

This effort objective was to demonstrate/validate environmentally-preferable (low-VOC, non-hazardous) coatings and depainting technologies. The goal was to qualify materials/processes for use on support equipment, launch structures, test stands, ranges, and any other carbon steel structures at CCAFS and KSC. Performance measures focused on the coatings ability to provide corrosion protection under two conditions: ambient conditions on the Mobile Support Tower; and moderate heat and launch exhaust resistance on the Fixed Umbilical Tower.

The project approach involved the selection of alternative coatings based on prior NASA and USAF testing. The coatings would be applied to active launch complexes, and then evaluated, ideally after each rocket launch from the pad (Figure 13). The alternative coatings selected and tested were: two TSCs (zinc and aluminum-magnesium); one ablative; three low-VOC liquid coating systems; and one topcoat for the TSCs. The TSCs were of keen interest because, while they are approved for use, their ability to withstand launch conditions is not well understood.

Figure 13. *USAF CCAFS flame deflection trench at space launch Complex-6.*

The tested ablative (GE silicone) passed the acceptance criteria and is now widely accepted and used across KSC and AFSPC locations. The data showed that the other coatings, including the TSCs, however, do not adequately protect surfaces from extreme heat and corrosion without an ablative or seal coat over top. Nonetheless, NASA benefited from this project through the generation of operational data on coatings that had been added to the NASA-STD-5008B APL as a result of previous TEERM coatings studies (specifically the TEERM Isocyanate-Free Coatings project). The project also brought renewed interest within NASA and the USAF to further evaluate TSCs and other coating combinations (Lewis, 2007a). The data also showed that the blast and recovery unit performed well for large coating removal/surface preparation tasks and media blast material containment.

7.5 Ozone Depleting Substances, Solvent Substitution, Aqueous Based Cleaners and Volatile Organic Compounds

Domestic and international regulations and policies are driving the replacement, stockpiling, and reuse of ODSs in NASA operations. Several materials present specific challenges for replacement because of their common use in NASA systems and facilities. For example, since 2014, one commonly used solvent, HCFC 225, is no longer available for purchase. R22 is becoming increasingly expensive, production and import has been decreasing since 2015, and new R22 and the equipment using the solvent will be phased out in 2020.

Replacement materials must meet toxicity and performance requirements, be environmentally-friendly, and contain low or no HAPs or VOCs. NASA faces many challenges in implementing green substitutions for ODSs, including identifying materials that meet flammability, material compatibility, and performance requirements as well as making the identification and substitution of materials a priority.

Continued use of chlorinated solvents increases costs associated with facility compliance, spills and cleanup costs, and launch systems lifecycles. Increasing regulatory pressure, both domestically and internationally, has affected availability and acceptability of solvent alternatives. Alternative solvents and processes that have been qualified are often not robust enough for many facility applications, or, as is the case with aqueous-based processes, may generate large amounts of wastewater. Facilities have incurred additional costs and potential health and environmental risks because of lack of a standard solvent substitution process. Regulatory drivers include:

- REACH
- CAA Title VI
- EO 13693
- NASA Strategic Sustainability Performance Plan

7.5.1 Consumer Guide to Alternative Parts Washers

The AP2 Program Office led a project with five NASA centers and the Rochester Institute of Technology to evaluate environmentally-preferable parts washers and chemistries. The AP2 Program Office developed a “Consumer’s Guide to Alternative Parts Washers” to assist environmental managers, shop owners, and procurement personnel in deciding which environmentally-preferable parts washer would work best for their shops. Each chemistry includes information about chemical characteristics, cleaning efficiencies, VOC content, and cost. Charts allow for quick identification and comparison among alternatives.

The guide covers 53 alternative and 4 benchmark chemistries (MEK, mineral spirits, isopropanol, and acetone) each of which was lab-tested to determine cleaning efficiency. The document also covers nine alternatives that were demonstrated at KSC, GSFC, Michoud Assembly Facility (MAF), MSFC, and WFF in detail. To date, four of the nine shops that tested alternatives have decided to purchase their test chemistries or other alternatives recommended by the guide, and several other shops are considering doing the same. The project resulted in significant cost avoidance. Seven of nine units and chemistries were provided for the onsite test period by vendors. The 57 laboratory-tested chemistries were also provided as in-kind by vendors. The AP2 Program Office also received in-kind contributions from the Rochester Institute of Technology that allowed testing for an additional 21 chemistries.

7.5.2 Portable Laser Coating Removal

NASA participated in an ESTCP project focused on validating a removal system using a PLCRS. PLCRS removes coatings with minimal environmental and safety impact, and there are no harmful chemicals that need to be purchased, stored, used, or disposed. Low-power, lightweight, handheld portable laser systems were selected based on their performance during screening tests and on commercial-off-the-shelf availability. Three laser systems were chosen: carbon dioxide, Neodymium: Yttrium-Aluminum-Garnet (Nd: YAG), and diode. Testing requirements included demonstrating the effectiveness of coating removal from typical aerospace materials without causing damage to the substrate.

The Nd: YAG portable laser system performed the best and had the best ease of use. The technology was validated as an effective and environmentally-safe alternative to existing depainting processes, and substrate materials were not significantly affected.

NASA and DoD use various types of coatings and paints on airframes, components, and GSE primarily for corrosion protection. Removal and reapplication of these coatings is necessary for reasons such as surface inspection or replacement of damaged or degraded coatings. Current methods for small area and supplemental removal of coatings have included the use of hazardous solvents, abrasive blast media, and hand sanding. These methods are costly, time consuming, labor-intensive, and often result in undesirable environmental conditions including the release of VOCs, particulate matter emissions, and dust.

The results of this project led to an intensive series of field demonstrations at GRC, WPAFB, and KSC. Lasers were tested on a variety of GSE from several NASA centers and Boeing for use on several types of Orbiter hardware including tile cavity applications.

The PLCRS showed excellent potential for implementation for non-destructive evaluation and inspection of weld-lines and for small-area depainting/corrosion removal where blast-media is not permitted. The demonstration proved that PLCRS can reduce critical GSE down-time, thus increasing mission readiness while reducing the risk of contamination that can arise when using some conventional methods of removing coatings (Rothgeb and McLaughlin, 2008).

7.5.3 Oxygen Cleaning Studies

Historically, solvents have been the chemicals of choice for NASA, DoD, and the aerospace industry for cleaning aviation oxygen systems and related components. Many of these chemicals have been classified as ODSs and are therefore regulated by the CAA and Montreal Protocol, which have set finite caps and phase-out dates for their manufacture and use.

Maintaining the cleanliness of oxygen lines is paramount to the safety and well-being of aerospace vehicle crew. When contamination is discovered, the lines must be cleaned. This process used to entail dismantling and removing the oxygen lines from the aircraft, cleaning with CFCs and HCFCs, and then reinstalling on the vehicle. This procedure resulted in emissions of ODSs, high labor costs, and long periods of aircraft downtime.

7.5.3.1 Joint Group on Pollution Prevention Oxygen Cleaning Study

NASA participated in a JG-PP project aimed at demonstrating, validating, and qualifying multiple technologies that would eliminate the use of ODSs and result in cost avoidances. Two technologies were chosen for testing, Hydrofluoroether (HFE)-7100 and an aqueous cleaning system. HFE-7100 was used in a transportable onboard solution as a direct replacement for the ODSs, while the aqueous cleaning system was used in several off-board demonstrations. Both solutions met the acceptance criteria from the JTP and modified testing specifications from the JTR.

It was estimated that these alternatives can result in cost avoidances of as much as $1M per aerospace vehicle by eliminating the consumption and emission of tens of thousands of gallons of CFCs annually and reduction of labor costs and aircraft downtime. These technologies can also potentially be applied to other applications such as oxygen lines for tanks, machinery, and hospitals.

NASA’s participation in the project included assistance in developing the JTP and identifying suitable cleaning products for testing. NASA had full intention of implementing; however, at the conclusion of the project, many NASA centers had already implemented their own non-ODS cleaning technology or other solutions. Knowledge gained from this project was used in a follow-on project to evaluate next-generation oxygen system cleaning products as substitutes for Class II ODSs such as HCFC-141b.

7.5.3.2 NASA Precision Cleaning of Oxygen Systems and Components Study

TEERM teamed with Yale University and WSTF in a two-phase project to evaluate new oxygen cleaners and overcome existing barriers of using Class II ozone depleting substances as qualified cleaning agents for oxygen systems and related components.

Based upon a literature review, a list of potential alternative solvents was generated. This list included several well-known and established aqueous/surfactant solutions used for non-oxygen degreasing applications as well as a variety of fluorinated compounds that are expected to be compatible in an oxygen environment. Potential alternatives were evaluated in a phased project that determined the level of fluorination in fluorocarbons necessary to mitigate flammability issues. Non-Volatile Residue (NVR) testing was done on fluorinated/perfluorinated molecules and anionic/nonionic surfactants. Surface roughness inconsistencies of coupons led to suggested modification of the NVR testing procedure.

Preliminary results with fluorine atoms indicated that cleaning efficacy is unchanged. The design solution is elusive, with tradeoffs impacting cleaning efficiency, flammability, and environmental persistence. Other properties such as oxygen compatibility, miscibility, vapor pressure, and boiling point are also important criteria. All promising categories identified by Yale would require additional modeling, investigation, and fine-tuning before testing (McLaughlin, 2009).

7.5.4 Precision Cleaning and Contamination Control Group

Many precision cleaning agents used by NASA are categorized as Class 1 or Class ODSs and have been banned from production and/or use, while others will be phased out in the future. In response to this obsolescence risk, NASA formed a Precision Cleaning and Contamination Control Group led by NASA WSTF and co-chaired by TEERM. The group’s objective is to maintain a peer-driven network of individuals, engaged in precision cleaning and contamination control issues, who come together to share their collective knowledge and learn from one another. Members work together to identify common problems and explore solutions, to develop and implement best practices, and seek to advance precision cleaning technology.

The group participated in the DoD’s Joint Service Solvent Substitution Working Group. The collaboration has resulted in MSFC performing a lab scale study funded by the U.S. Army to look for replacements to n-Propyl Bromide for vapor degreasing applications. MSFC also completed a study of alternatives to HCFC 225 (Mitchell and Lowrey, 2015).

7.6 Lead in Electronics

Following the EU RoHS Directive, many industry suppliers began eliminating lead in solder, electronic components, and circuit board finishes. There are no requirements for electronic component manufacturers to change their labeling to differentiate between traditionally processed devices and those processed using lead-free technologies. Lead-free electronics [solder, component finishes, Printed Wiring Boards (PWBs), etc.] bring new failure modes in electronics. Risks to the NASA mission include potential loss of qualified material resulting in reduced performance of available replacements and the associated costs and schedule impacts.

While solder reliability data have been generated by the commercially electronics industry, much of the data was for testing mainstream lead-free solder alloys, SAC305, SAC396, and SN100C. Reliability data was needed for newly emerging lead-free alloys to determine if they could survive the harsh use environments of aerospace and military applications.

Finally, attempts to continue using traditional tin-lead solder during the transition period presents its own risks, such as compliance with current and future environmental regulations, risk of cross-contamination during rework, and component obsolescence of lead surface finishes. Regulatory drivers include:

- RoHS Directive
- WEEE
- REACH

From 2001 to 2017, the NASA TEERM Program Office planned and executed three lead-free electronics testing projects and conducted assessments of NASA solder operations and risks associated with lead-free solders.

NASA's interest and concern about lead-free solder took off in mid-2002 following an email message from the TEERM office sharing a story about a military contractor's unintended receipt of lead-free electronics parts where lead-containing parts were specified. Shortly thereafter, the Space Shuttle Reusable Solid Rocket Motor program reported receipt of lead-free off-the-shelf electronics parts. The SEA Initiative began closely following the Joint Council on Aging Aircraft (JCAA)/JG-PP lead-free solder project, which TEERM began managing in 2002. SEA viewed the lead-free solder issue as two separate problems: 1) the potential for Shuttle to receive parts that failed to meet specifications; and 2) the need for testing and qualification of lead free solders that meet Shuttle requirements. A representative from the NASA Electronics Parts and Packaging (NEPP) Program was identified to interface with TEERM on its lead-free activities.

The first of the three testing efforts was a partnership, under the auspices of JG-PP and, later, the JCAA, to begin tackling the reliability issues surrounding lead-free electronics in high reliability applications. The genesis of this first project was a white paper written by Raytheon Systems Company to the DCMA as a response to the ban on using lead in solders used in the electronics industry. The first ban was to occur in Europe in January 2008 based on a draft document being created at the time in the EU. The Japanese industry has made considerable progress and four firms were already producing electronic equipment with lead-free solders. Additionally, President Bush had recently signed EO 13423 that included a mandatory 50% lead reduction use by federal agencies by 2005.

The objective of three TEERM lead-free solder projects was to generate comprehensive test data on the reliability of circuit cards newly manufactured and reworked with lead-free solder and subjected to simulated high-reliability [Institute for Printed Circuits (IPC) Class 3] environmental conditions. The joint group agreed that the projects should:

- include both manufacturing and rework of circuit cards;
- address aerospace performance requirement; and
- encompass new and legacy defense and space systems.

Table 5 summarizes the solder alloys examined in each of the three projects.

Table 5. *Solder alloys evaluated in TEERM lead-free solder projects.*

Project	Project Focus	Comment
Lead-Free Solder Testing for High Reliability Electronics (Project 1) (JCAA/JG-PP) (2001 – 2006)	Solder-joint reliability (laboratory) testing of lead-free solder alloys on newly manufactured and reworked circuit cards.	• Project completed • Lead-free alloys: ○ Sn-0.7Cu (for wave soldering) ○ Sn-3.9Ag-0.6Cu (for wave, reflow, and manual soldering) ○ Sn3.4Ag-1.0Cu-3.3Bi (for wave, reflow, and manual soldering)
NASA-DoD Lead-Free Electronics Project (Project 2) (2006 – 2011)	Solder-joint reliability (laboratory) testing of lead-free solder alloys on circuit cards reworked with tin (Sn), lead-free and mixed (lead/lead-free) solder alloys.	• Project completed • Lead-free alloys: ○ Sn-3.0Ag-0.5Cu (SAC 305) (for reflow and manual soldering) ○ Sn-0.7Cu-0.05Ni+Ge (SN 100C) (for wave, reflow, and manual soldering)
Lower Process Temperature Lead-Free Solders (2012-2016)	Test low process temperature bismuth-containing lead-free solders to determine if they reduce failure associated with pad cratering.	• Project in work by stakeholders, without TEERM • Lead-free alloys: ○ Sn 3.4Ag 4.8Bi ○ Sn3.5Ag1.0Cu3.0Bi ○ Sn2.25Ag0.5Cu6.0Bi ○ Sn2.0Ag7.5Bi

Although each TEERM lead-free solder project had a unique purpose, they all had similar elements. Each project focused on lead-free solder alloys testing on Plated Through Hole (PTH), Surface Mount Technology (SMT), and mixed technology circuit card assemblies (Figure 14). The anticipated outcome of each project was that validated solders would then have the potential to be transitioned to new program hardware, Original Equipment Manufacturer (OEM) processes, and other depot and field-level facilities. The approach for each project involved bringing together defense contractor representatives and representatives from the affected military systems and depots to collaborate in selecting solder alloys, testing the most promising alloys to a test protocol created by the group, and assessing the results for possible implementation. Each project culminated with the development of a JTR documenting the data and testing results. Engineering authorities can refer to the lead-free solder testing results during design decisions for specific military and space systems.

Among the key findings from these lead-free studies was that joint reliability is dependent on a combination of factors, two major ones being component type and exposure environment. For some component-environment combinations, lead-free solders were found to be as reliable as the currently used tin-lead solder. In other cases, lead-free solders failed before the tin-lead control.

One of the things that made these TEERM lead-free solder projects unique was the decision to look at rework effects on solder joint reliability. Rework can be a major problem in conversion to lead-free solder for aging legacy space and weapons systems. The consortium agreed that rework procedures would be critical in evaluating intermetallic contamination that may occur during rework procedures involving the lead-free rework of tin-lead assemblies. Intermetallic contamination between lead-free solder alloys and eutectic tin-lead solder could cause premature failure of lead-free solder joints.

Lastly, all the lead-free solder projects relied heavily on direct and indirect contributions from multiple partners. Each project involved technical representatives from dozens of government and private entities. The first TEERM lead-free solder project involved 95 organizations, of which 24 were international. There was a 7:1 return on NASA investment in these projects and total in-kind contributions of $3.0M due to the time donated by the core OEM- team in developing the JTP, JTR, and designing the test vehicle.

The team members on TEERM’s lead-free solder projects were extensive, comprising USAF, Army, Navy, Marine Corp, DLA, and major aerospace and defense contractors (see Table 6). TEERM also interfaced with major consortia, associations, and working groups on matters of lead-free solder (see Table 7). These forums provided an effective means for TEERM to learn about ways to reduce electronics reliability risk resulting from the global movement toward lead-free solder alloys and surface finishes, and a means to disseminate the findings from TEERM’s lead-free projects. On occasion, TEERM would support NASA in hosting lead-free consortia meetings, as it did for a meeting at KSC of the DoD-led Lead-free Solder Environmental Risk Mitigation Team.

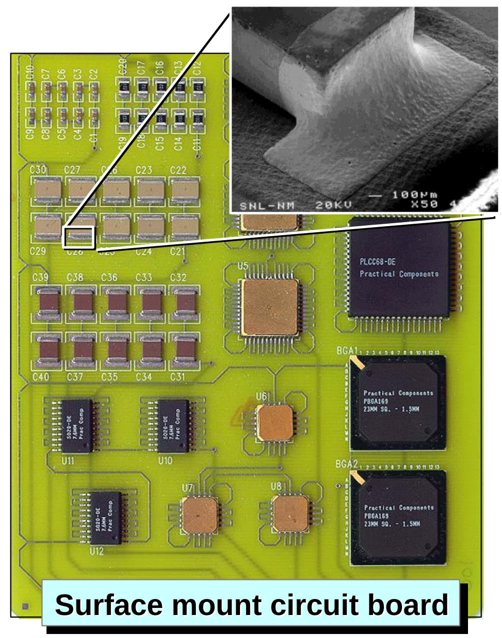


Figure 14. *Surface mount circuit board.*

In addition to the testing projects, NASA TEERM performed a NASA solder operations assessment, publishing a report in April 2003 (Rothgeb, 2003). The study was performed to determine the types and severity of risk relating to electronics manufacturing with lead-free solders to NASA programs present and future. Several site visits were performed within NASA center shops that used the highest volume of lead-based solders. Qualitatively, each Center’s programs were reviewed for the risk of intrusion of lead-free systems into their process lines and/or the risk to NASA of obsolescence should the electronics industry shift to lead-free systems soon. The study found that NASA’s highest risk exists in future programs should the industry convert to lead-free systems. There are not enough resources within NASA to support the construction of a next generation reusable launch vehicles or to maintain those systems without outside electronics manufacturers’ involvement. Should the industry discontinue support of conventional lead solders and an alternative to conventional lead-based systems is not qualified for aerospace (manned and non-manned systems), all NASA's high-reliability systems currently under construction and all future systems will be compromised.

The transition of the findings from these testing projects and studies throughout NASA and industry was a major focus towards each project end. TEERM presented data at various major electronics conferences, such as IPC Association Connecting Electronics Industries (APEX), Joint Federal Aviation Administration (FAA)/DoD/NASA Conference on Aging Aircraft, and

Surface Mount Technology Association (SMTA). The JCAA/JG-PP lead-free solder project won the 2005 Soldertec Lead-Free Solder award and international award.

Table 6. *Representative corporations, agencies, and universities with whom TEERM interacted during the three lead-free solder projects.*

U.S Interfaces	International Interfaces
• NASA Centers (KSC, JPL, MSFC, JSC, GSFC, Ames) • NASA Shuttle Contractors (USA – SRB, Boeing – Orbiter) • Alliant Tech Systems • BAE Systems • The Boeing Company • Celestica • Coffin Industries • Curtiss-Wright • DMEA • Foreside • General Electric (GE) • Garmin • General Atomics • General Dynamics • Goodrich • Hamilton Sundstrand • Harris Corp • Honeywell • ITL Circuits • ITT • Lockheed Martin • Lucent Technologies • Motorola • Northrop Grumman • Raytheon • Rockwell Collins • Texas Instruments • Air Force, notably the USAF Aging Aircraft Division, which provided significant funding • Army • Navy • Marine Corps • DOE/ SNL • University of Maryland • University of Tennessee • U.S.EPA Design for Environment • Heraeus, Indium, Interrail, Isola, Mitsue Comtel/Sonja Metals, Practical Components, Vitrinids, and other suppliers of solder alloys, electronic parts, and other test materials	• Atrium (U.K.) • BAE Systems (U.K.) • C3P (Portugal) • INASMET (Spain) • ISQ (Portugal) • ESA • MBDA (U.K.) • Office of Naval Research International Field Office (ONRIFO) (U.K.) • Secom (Portugal) • The Welding Institute Ltd (U.K.)

Table 7. *Representative collaborative initiatives with whom TEERM interacted during the three lead-free solder projects.*

U.S. Interfaces
• JG-PP
• JCAA
• AIA-GEIA-AMC Lead-Free Electronics in Aerospace Project (LEAP) Working Group [Aerospace Industries Association (AIA) Government Electronics and Information Technology Association (GEIA) Avionics Maintenance Conference (AMC)]
• American Competitiveness Institute
• Circuit Card Assembly and Materials Task Force
• Industry and Government Executive Lead-Free Cooperative Integrated Process Team (ELFIPT)
• Lead-free Solder Environmental Risk Mitigation Team
• NASA EEE Parts Program at GSFC
• NASA TEERM
• National Center for Manufacturing Sciences
• National Institute of Standards and Technology (NIST)
• National Electronics Manufacturing Initiative
• NASA SEA Initiative
• University of Maryland Computer Aided Life Cycle Engineering (CALCE)
International Interfaces
• ANIMEE (Portugal)
• Global Environmental Coordination Initiative (GECI) (International)
• ILTAM
• Low Cost Lead-Free Soldering Technology to Improve Competitiveness of European SME (LEADOUT Project (EU))

Project data was also distributed to the following organizations for inclusion in their own work products:

- ***SEA Initiative*** – SEA issued a white paper in June 2007 that concluded the Shuttle program should consider taking several steps to mitigate the risk of lead-free parts infiltrating SSP electronic systems.
- ***MSFC Lead-free Technology Experiment in Space Environment*** – The objective of this NASA MSFC-led project was to determine the effect of launch, re-entry and low-Earth orbit conditions on the reliability of lead-free soldered electronic components. Lessons learned from TEERM's lead-free test vehicle helped MSFC in designing its test vehicle. A box containing the circuit cards was launched on STS-129 in November 2009 and affixed to the outside of the ISS shortly thereafter, where it remained for 18 months. This study provided information useful to electronics engineers in determining lead-free parts compatibility in low-Earth orbit.
- ***IPC Industry Standard*** – Findings from the JCAA/JGPP Lead Free Solder Project were incorporated into the writing of Appendix B of the *Guidelines for Thermal Cycle Requirements for Lead-free Solder Joints* as part of the industry standard IPC-9701, *Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments*.
- ***AIA-ARINC-GEIA LEAP*** – JCAA/JGPP Lead Free Solder Project findings were used in writing GEIA-HB-0005-2 –*Technical Guidelines for Aerospace and High Performance Electronic Systems Containing Lead-free Solder*.

- ***Various research organizations***, such as the University of Maryland CALCE, SNL, CirVibe Inc., Defer Solutions, and Electronics Packaging Solutions International, conducted lead-free solder interconnect reliability modeling using data from TEERM lead-free solder projects.

Lead-free solder development is important to NASA to stay ahead of the changing electronics market and maintain a high level of environmental stewardship. The continued use of solder containing lead could have major consequences including, but not limited to, compliance with current and future environmental regulations, concerns about legislation banning lead-containing products, risk of mission readiness, and component obsolescence with lead surface finishes. Collectively, the TEERM lead-free solder projects represent the most comprehensive and technically thorough studies to date of how promising lead-free solders perform under harsh aerospace/military environments. The results are being used by OEMs, suppliers, and system managers as they consider transitioning to lead-free materials in electronic assemblies. References include Kessel, 2009a; Kessel, 2009b; Kessel, 2011a; Kessel, 2011b and Kessel, 2016b.

8 Projects with Energy and Sustainable Development Focus

8.1 Alternative Energy Use Solutions

While seeking to increase their use of alternative energy sources, NASA centers encounter challenges related to increasing costs, energy security, a legacy of spent resources, and traditional way of performing activities with aged infrastructure and traditional energy sources. The electric grid can be unreliable and its security unpredictable, leaving day-to-day operations and mission critical activities vulnerable. Alternative energy sources provide an avenue for energy security. Regulatory drivers include:

- EISA 2007
- EO 13693

TEERM has worked with NASA Centers, DOE, and international partners to identify technologies that can help increase alternative energy use and improve energy security. Specific examples include the JSC Building 12 Wind Turbine Study, and the planning studies at Svalbard and Poker Flat Research Range (PFRR).

8.1.1 Johnson Space Center Building 12 Wind Turbine Study

TEERM engaged NREL to include JSC's Building 12 wind project in their DOE funded study (Fields et al., 2016). The NASA Building 12 project is unique among the case studies conducted by NREL as this project involved detailed pre-construction and post-construction measurements (Figure 15).

The JSC Building 12 wind turbine installation was originally designed as an effort to further the sustainability practices of JSC through a high-visibility education and demonstration project. The goal was to provide onsite generation while aiding in compliance with mandates regarding renewable energy production at federal buildings.

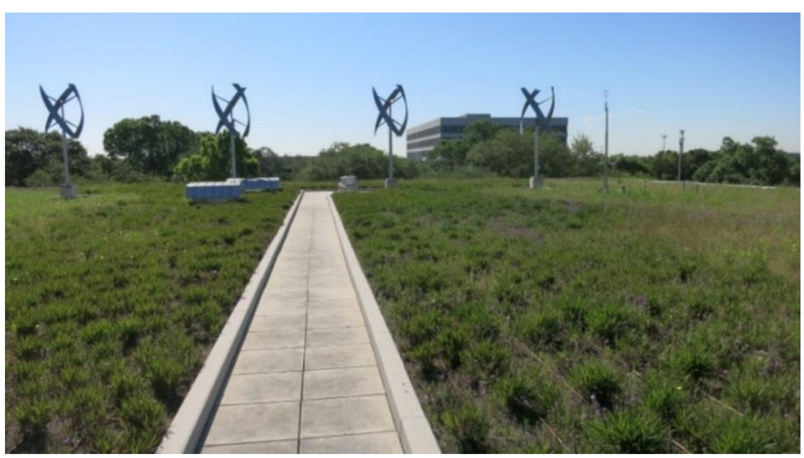


Figure 15. *JSC Building 12 wind turbines*

Completed in December 2014, the NASA Building 12 installation consists of four Urban Green Energy Eddy GT turbines. The project was constructed as part of a larger Building 12 renovation that included other sustainability initiatives such as a green roof (Section 8.3). Partners in this project included TEERM, JSC, and NREL. NREL funded wind and green roof instruments and installation under an Interagency Agreement signed January 14, 2014 (for 2 ½ yrs., 2014 to 2016).

NREL researchers initiated a measurement campaign consisting of multiple rooftop anemometers and other atmospheric instrumentation located on the prospective turbine pad mounts and in the immediate rooftop vicinity. The Building 12 measurement program consisted of two phases: pre-construction measurement campaign and post-construction measurement campaign. Although the Phase I assessment revealed that the site has a low wind resource (<2 m/s), the project moved forward with Phase 2, which included four Eddy GT turbines installation.

Since installation, the project has been hindered by low production. This hindrance can be attributed to the resource not matching the required cut-in speed for the technology to begin generating power (~3.5 m/s). Additionally, the turbines have not produced as much power as even the low winds would predict using a simple convolution of the wind speed frequency distribution with the wind turbine power curve. The belief is that the inverters represent discrepancy in the expected power from wind speed measurements versus actual turbine power measurements. The inverters require a sustained minimum wind speed to function. This minimum duration is often not achieved, and the energy produced from the turbine is converted into heat energy for system protection. This setup is sometimes known as a dump load. The low wind speeds combined with the inverter setup mean that the NASA Building 12 turbines are performing well below their anticipated generation and even their potential as measured with wind speed. This low performance demonstrates the critical link not only between anticipated generation and onsite measurements but also the need to account for losses as part of the energy estimation process.

Study conclusions (NREL, 2016) indicated “It should also be noted that based on several key factors (i.e., wind speeds are typically lower and costs for implementing projects in built environments are typically higher), projects in the built environment can be difficult to justify on a cost of energy or energy-offset basis. Understanding the expected production of a wind turbine in the built environment is a very complex undertaking; the use of onsite resource measurements combined with high-fidelity models is likely the only way to truly understand the expected turbine production.” JSC Building 12 Wind Project developers feel that the installation did not meet all its goals primarily because of the location’s low wind resource, which led to installation overall underperformance.

8.1.2 Poker Flat Research Range

PFRR is a 5,132-acre scientific rocket launch facility located approximately 30 miles north of Fairbanks, Alaska, and operated by the University of Alaska's Geophysical Institute under contract to NASA’s WFF. In addition to launching sounding rockets, PFRR is home to many scientific instruments designed to study the arctic atmosphere and ionosphere (Figure 16).

In 2015, TEERM initiated an energy resiliency improvements study for supporting NASA missions/ projects at PFRR because of the site's remote high latitude location. There is potential to learn lessons from feasibility studies of microgrids, onsite generation, and operating cost reduction opportunities that can be instructive for other remote locations such as Svalbard in Europe. Stake-holders include University of Alaska Fairbanks (UAF) Geophysical Institute, UAF Alaska Center for Energy and Power; WFF, and ABB. While this project originated under NASA TEERM, the project is now ongoing under another task in support of NASA and involves monitoring ongoing data collection activity. This project overview provides the history and project status as of September 2017.

Figure 16. *Poker Flat Research Range.*

TEERM was instrumental in bringing into the project SMEs from the UAF Alaska Center for Energy and Power-Power Systems Integration Program to work with PFFR personnel for power usage characterization and potential resiliency and cost reduction improvements. This work combination also leveraged an established Integration Program's collaboration with ABB to support microgrid feasibility determination. This project has NASA support, solid stakeholders, and potential to include various technology solutions (microgrid, energy storage, renewable energy technologies, etc.), and could be applied at other locations using this approach (online research, interviews, local SME, feasibility study, etc.).

While PFRR is more or less contiguous geographically, electrical service is provided at a multitude of points. This ability carries with it the effect that the electric rate is not optimized for the total use. There are four major electrical meters. Actual time-series data from each of these services is required to understand the variability in demand at the meter, and to assess if energy storage and behind the meter generation may be economical in leveling the charges.

There is potential to make at least one part (upper or lower range) of PFRR into a microgrid with the potential to island during critical launch operations and in emergency situations. Both wind and solar power might be competitive options on the upper range. To determine an initial sizing assessment of assets (renewable generation, dispatchable generation, energy storage, both electric and thermal, and demand response) required to increase resiliency and reliability, and decrease cost of electricity, we need some baseline understanding of how/when/by whom energy is consumed on PFRR. In response to this need, WFF funded an effort at PFRR to collect a year's worth of baseline electrical consumption data from newly installed meters to allow for characterization and determination of demand charge potential savings. This data acquisition should complete summer 2018. The following features summarize site electric power characteristics:

- Lower and upper range are not fed through a single point of common coupling, but by separate 34.5 kV lines that combine quite far away.
- Critical loads during launch are located both on the lower and the upper range (two separate grids for all intents and purposes at this point).
- Two very large loads [(Advanced Modular Incoherent Scattering Radar (AMISR) and Imaging Radiometer] are on additional separate service drops from 34.5 kV line owned by the utility.
- Lower range is a 4160 V grid connected through a single meter, i.e., we will need to instrument the critical loads on this grid to understand their power draw.
- Upper range is a prime spot for Photovoltaics (PV) with a southern hill side unused and cleared on several acres.
- There is an empty building at the upper range that has all the needed environmental controls
- Close by is an electrically heated building (480 V service) with space in the utility room for electro-thermal storage (potentially).

Figure 17 presents a potential network topology.

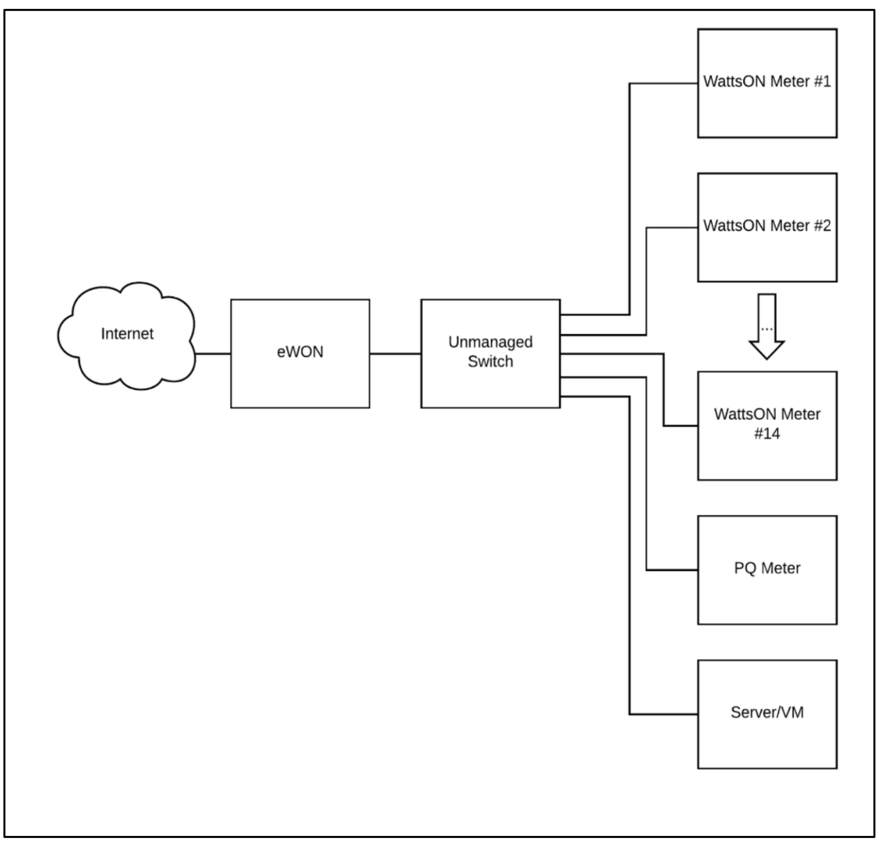


Figure 17. *Proposed network topology*.

8.1.3 Svalbard Satellite Station Renewable Energy Assessment

Svalbard Satellite Station (SvalSat) is located at 78.23°N 15.39°E, west of Longyearbyen, on the island of Spitsbergen, the largest island of the Svalbard Islands (Norway). Established in 1996, SvalSat is the world's largest commercial ground station with more than 31 multi-mission antenna systems. The SvalSat sister site, Troll Satellite Station (TrollSat), is in Antarctica and allows for unique, all-orbit support for polar operating satellites. KSAT operates both locations.

Assets from NASA and ESA are located at each site, which supports several mission critical functions encompassing NASA's fiber-optic link, Galileo, Near Earth Network, and Copernicus.

Because of their remote location, and extreme weather conditions, these sites are faced with unique challenges maintaining resiliency requirements, increasing sustainability, and reducing cost/risk for energy use. These sites depend on reliable energy sources and are limited by current power sources, impacting future expansion plans.

A coal-fired power plant built in 1983 supplies heat and electricity to Longyearbyen, including SvalSat. The aging infrastructure is of increasing concern to the Norwegian Government (power plant owner) and the local population dependent on reliable heat and power. The concern extends to NASA and ESA, which rely on this facility to power several mission critical functions at SvalSat.

Following a visit to Svalbard, TEERM identified four alternates to the use of coal to mitigate these risks.

- Solar Power. Solar appears to be a viable renewable energy option with some limitations. Good conditions exist overall for four or five months during the year. Maximum efficiency, however, requires an automated tracking system, and possibly a large array, to produce the +8 GWh/annually required for prime power.

- Solar/Wind Hybrid. Svalbard faces some relatively unique challenges maintaining resiliency requirements, increasing sustainability, and reducing cost/risk for energy use. Therefore, more than one renewable energy source will likely be required to maintain reliable electric and heat energy throughout the year. Based on current knowledge, a mix of solar power and wind power could be a viable combination of technologies. Designs would need to consider the limited availability of solar and less productive months for wind, to ensure capacity is maintained during all months of the year. Mounting wind turbines in permafrost locations could present a stability issue. In the future, geothermal energy could supplement solar and wind power if geothermal conditions are found to be acceptable.

- Geothermal. Geothermal energy has been successful in many locations when the thermal conditions are adequate. There has been increasing interest during the past few years in investigating the possibility of using geothermal energy on Svalbard; however, limited geothermal investigation has restricted progress. During a 30-year period from the 1960s to the 1990s, several deep exploratory wells for oil and gas on Svalbard were drilled (Science Daily, 2017). Some were approximately 3,000 m deep. In addition, data is available from the Longyearbyen CO_2 Storage Laboratory (University Centre, Svalbard) that has seven cored wells near Longyearbyen (http://co2-ccs.unis.no/default.htm). The deepest of these wells is 970 m. The quality of the existing subsurface temperature measurement is uncertain. Permafrost affects temperature measurements, so more advanced temperature sensing techniques may be required (Science Daily, 2017). More geothermal investigation is required before considering geothermal energy as a viable renewable energy option for Svalbard.

- Fuel Cells. A recent study suggests that ship transporting of hydrogen supplied as liquid hydrogen from mainland sources could be considered as another alternative for direct hydrogen fuel cells power generation.

With an ever-increasing focus on resiliency and energy security, interest remains by NASA, ESA, KSAT, and the Norwegian Space Agency (NSC) to reduce the risks seen at SvalSat. NASA has a continued interest in Svalbard and is working with the Norwegian Map Authority to develop a laser ranging station there (Photonics, 2017). Studies on potential replacements for coal at Svalbard are ongoing (ScienceDaily, 2017).

8.2 Fossil Fuel Conservation Solutions

By 2020, NASA aims to meet the following goals established to ensure the continued availability of resources critical to the Agency mission and reduction of fossil fuel use: 1) reduce energy intensity of facilities; and 2) produce or procure energy from renewable sources. Regulatory drivers include:

- EO 13693
- EISA
- NASA Strategic Sustainability Performance Plan

TEERM has worked with NASA centers, DOE, and with our international partners to identify technologies that can support fossil fuel conservation. A specific example is the “KSC Hydrogen Fuel Cell Mobile Lighting Tower Demonstration” project.

8.2.1 KSC Hydrogen Fuel Cell Mobile Lighting Tower Demonstration

Diesel fuel generators power most mobile lighting units today. These systems are not environmentally-friendly, and their noise can create a safety hazard for workers who are unable to hear (such as oncoming traffic in road construction applications) because of the decibel levels produced by the diesel systems. The units typically provide lighting as well as auxiliary power for items such as power tools and air conditioners. NASA uses diesel generator light tower sets for various tasks at security gates, launch viewing sites, fallback areas, bus inspections, outage support, and special events.

In 2010, TEERM became aware of a project led by DOE SNL to support commercialization of a Hydrogen Fuel Cell Mobile Light Tower (H_2LT) (Figure 18). TEERM arranged for the KSC mobile power systems group to use the system for typical uses during the evaluation period so that sufficient run time and environmental exposure were experienced. TEERM facilitated the signing of a bailment agreement between NASA KSC and SNL in 2011 to conduct operational testing of the unit at KSC. Throughout the demonstration, TEERM served as SNL's primary NASA point-of-contact, securing the support of safety and other KSC technical personnel and providing funding to the KSC propellants group to supply the necessary hydrogen fuel. The unit was at KSC from April 2011 to September 2012. Key project partners included KSC, SNL, Multiquip, Altergy, Luxim, and Straylight.

Figure 18. *Hydrogen fuel cell mobile lighting tower.*

NASA and DOE wanted to evaluate and document the performance of a new mobile tower lighting system that pairs a Proton Exchange Membrane (PEM) hydrogen fuel cell with plasma lamps to gain life expectancy data in a hot, humid, and corrosive environment that are characteristic of the KSC location. This system also achieves significant noise reduction and can be used in a building interior. KSC was one of five sites selected by the team to evaluate the unit's performance in four key areas:

- Lighting efficacy (illumination uniformity, glare, visibility, coverage area)
- Emissions (compare with diesel system, assess H_2LT)
- Refueling efficacy (refueling time, ease of operation, costs)
- Design robustness (engineering analysis of performance, other testing)

The H_2LT was used at KSC for one year, including at the international press area during the last launch of the Space Shuttle Atlantis. After a year of use in the hot, humid and salty air, the system performed without failure. NASA corrosion engineers inspected the H_2LT and reported their observations to Multiquip.

DOE reported that the fuel cell mobile light achieved a run time of 66 hours and a 73% reduction in GHG emissions compared to current technology. The units also generated no discernable noise. A commercial fuel cell mobile light system based on this design is now commercially available by Multiquip Inc. (Klebanoff and Devlin, 2011).

The Federal Laboratory Consortium (FLC) and DOE recognized this project team, including TEERM, for excellence in technology transfer:

- 2012 FLC National Award for Excellence in Tech Transfer, for "Fuel Cell Mobile Light Project," May 3, 2012.
- 2011 DOE Hydrogen and Fuel Cells Program Research and Development (R&D) Award, "In recognition of outstanding contributions to Fuel Cell Market Transformation Activities," May 11, 2011.

8.3 Sustainable Construction

TEERM has worked with NASA centers and our international partners to identify technologies that can increase the use of sustainable construction practices. Specific examples include the "Green Roof Storm Water Management at JSC" project and the "NASA and C3P Collaboration on Sustainable Construction Practices (ECOS) Study."

8.3.1 Green Roof Storm Water Management at Johnson Space Center

In 2012, JSC's Building 12 was rebuilt as a Leadership in Energy and Environmental Design (LEED) gold office building (Figure 19). This design included green roof and roof-mounted wind turbine (Section 8.1). A green roof can reduce the quantity of storm water released from the site from longer retention of roof-collected rainwater in the growing soil medium, thus helping the local waterways and aiding the local municipality**.**

TEERM introduced NREL wind researchers, university green roof researchers, and JSC sustainability team members, which led to a cooperative data collection project. NREL funded wind and green roof instruments and installation under an Interagency Agreement signed January 14, 2014 (for 2 ½ years). Project partners included JSC, Portland State University, University of Maryland, NREL and Carnegie Mellon University. An overview of the plans for this green roof study were presented at the NASA sponsored international workshop held at KSC in October 2014 (Starry, O. *et.al.*, 2014).

Building 12's green roof has an area of 35,000 sq. ft. The total plant count was approximately 67,413 planted in an 8-inch triangular pattern with an even mix. Plant coverage was about 50% of the roof after one year and 80% after 2 years. There are 1.2 million pounds of growing media (soil).

Environmental data were logged every 5 minutes and soil temperature and moisture data (Echo-TM, Decagon Devices, Inc.) collected every 15 minutes along drainage transects on each roof. Data were transmitted via EM50G nodes every six hours to a cloud server (Decagon Devices, Inc.) and the data downloaded and imported at the University of Maryland in College Park (UMCP) using software (Sensorweb) that was custom designed through collaboration with Carnegie Mellon University.

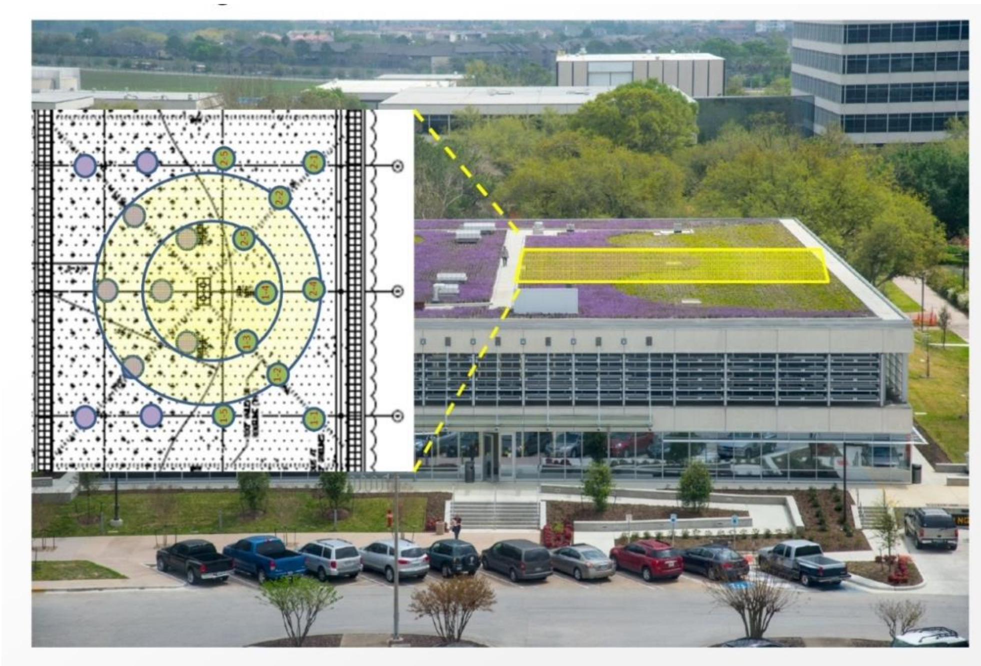


Figure 19. *JSC Building 12 green roof.*

Green roof researchers from Portland State University and UMCP are analyzing the data from the JSC roof as well as similar data sets from locations in Maryland, Pennsylvania, and Oregon. A major goal of this work is to determine whether the mechanistic model these researchers developed to predict green roof performance is robust across different climates. The JSC roof will be an especially interesting case study because of the anticipated high wind speeds there as well as the summer heat. As the researchers work to refine their models, they will be able to make predictions about how components like roof design features and irrigation scheduling can be fine-tuned to optimize green roof benefits associated with storm water management, energy efficiency, and possibly even wildlife habitat. The green roof moisture instrumentation has already been effective in reducing the irrigation system water usage by 80% (A. Sorkin, 2015; phone conversation with O. Starry, Portland State University).

8.3.2 NASA and C3P Collaboration on Sustainable Construction Practices

NASA and C3P leveraged information from the ECOS 1 Project in Portugal (Figure 25) to document and assess energy and sustainable construction technologies and best practices of mutual interest for reducing the environmental impact of a building throughout its lifetime, while optimizing its economic viability, as well as the comfort and safety of its occupants. TEERM provided support as stipulated in the execution of NASA specific responsibilities in a Space Act Agreement (SAA) dated October 13, 2010 between NASA and C3P.

This task's focus was on collection and assessment of innovative technologies and documentation of best practices proven to increase the energy efficiency of new and retrofitted buildings (including historical buildings) using renewable energies (e.g., solar, wind, wave, biomass, and hydrogen) and higher efficiency products/technologies. This NASA-C3P task outcome was a shared understanding and acceptance of new technologies and practices that may become new building design templates for sustainable construction.

C3P provided details of various ECOS community buildings for which NASA inputs were requested. NASA experience with related building sustainability

factors were identified and NASA sites with new or retrofitted buildings achieving LEED ratings were studied for relevant design features and operational practices of potential interest to the ECOS sites. A table of all such items was prepared with linked site-specific information that C3P could disseminate to the relevant ECOS sites. A determination was made of which non-NASA U.S. sources were appropriate to contact for supplemental building sustainability information that were potentially useful in Portugal. C3P specified the information that they felt to be of maximum benefit to the ECOS project from these sources. TEERM then contacted each source to determine what specific information they were willing to provide to support this activity. In various cases, the responses were direct ECOS site-specific suggestions, but most provided existing documentation of their building sustainability experience. C3P consulted with each identified community to select the most relevant information to use. TEERM researched and aggregated all requested information in a concise summary form with references for review. C3P selection of highest priority topics from this summary lead to more detailed information collection and dissemination.

Data provided to C3P included information from NASA Ames on their solar hot water system and other documents related to sustainability projects at Ames. JSC provided information on its solar hot water system as well as an energy summary and a report on JSC's use of renewable energy. KSC data included designs for a Green/Platinum Building and a description of the sustainable features of KSC's propellants facility. TEERM also provided information from the General Services Administration (GSA) including sustainability standards and information on minimizing environmental impacts.

The following list contains sites in Portugal TEERM visited in November 2011.

- *Beja* –Municipal building renovation in the historical district of Beja had started one month before the visit.
- *Moura* – New buildings being completed for Logica EM PV panel testing labs and offices were the subject of the Moura visit.
- *Peniche* – A tour was conducted of a new building under construction for surfing sporting events and training at the seaside location. Sustainable construction methods and materials were being used.
- *Torres Vedras* – A school was visited that had various energy-related upgrades including solar PV, solar hot water, Light Emitting Diode (LED) street lighting, etc.

C3P previously identified priority for this activity as the two ECOS community projects at Torres Vedras and Beja. As a result, TEERM examined where inputs could have the best opportunities for usefulness by the project teams that were already well underway with the implementation phase of their projects.

In the case of Torres Vedras, the social housing solar water system was determined to be best for experience-sharing. Both Ames and JSC solar hot water systems were used to provide suitable inputs. Beja's municipal building project had historical preservation aspects that were best linked with inputs received from GSA including GSA Facility Standards and briefings on sustainability and minimizing environmental impacts. An additional area of potential usefulness was NASA KSC's experience with increased energy efficient elevators since the referenced municipal building was found to have two elevators planned for installation.

The ECOS project in Portugal was characterized as receptive to NASA inputs/suggestions. Project participants, however, were not adequately prepared to respond when suggested approaches to energy-related enhancements were submitted. These findings may lead to these sites meeting sustainability goals, reducing use of non-renewable resources, and realizing cost savings.

9 Lessons Learned

TEERM's successful approach to evaluating new technologies has resulted in a number of lessons applicable to other programs evaluating new technologies. Lessons learned encompass:

- **Collaboration Increases Technology Evaluation Efficiency**
  A collaborative approach to solving environmental and energy problems is an effective approach to technology evaluation. Collaboration benefits project members through shared resources, increased confidence in results, and faster implementation of qualified technologies.
- **Communication is Key to Successful Workshop**
  TEERM determined that communication is the key to a successful workshop. TEERM starts engaging with NASA, potential workshop presenters, points of contact at the event location, SMEs, and university students six months prior to the workshop. Proactive communication and planning is significant, especially when engaging contacts located in Europe.
- **Applying Methodology to Resiliency Projects**
  The TEERM methodology for project development and execution will work for projects whose anticipated outcome is to achieve infrastructure resilience through sustainability.
- **Ensure Buy-In from Key Personnel**
  When dealing with very complex projects, especially those involving the processing of hazardous waste, it is important to ensure that there is strong advocacy from high ranking managers and decision makers at project start.
- **Limitations of Current Specifications and Standards**
  NASA specifications, drawings, and drawing notes are insufficient regarding hexavalent chrome-free conversion coatings. When developing new projects, project managers should provide the data NASA will need to modify specifications, drawings, and drawing notes.
- **Limitations of Vendor-Recommended Procedures**
  When preparing materials for testing (especially conversion coatings: chrome and chrome-free), the vendor-recommended procedures may not be adequate or refined, and process optimization may be necessary.
- **Increase Customer Interactions**
  Schedule regular customer updates and meeting throughout the project duration. Additional customer interaction can result in positive feedback and additional project support.
- **International Projects Require Better Understanding of Results Implementation Impediments**
  At project inception, be pro-active in assessing how project results can be implemented effectively and potential impediments addressed in the project planning.
- **Consider Already-Established Design Studies**
  When new building designs are targeted for advanced energy technologies consideration, the earliest design studies (before project schedule and costs are determined) should be the starting point for such activity to avoid adverse schedule and cost impacts that impede adoption.

10 Summary and Recommendations

TEERM benefitted NASA by identifying and evaluating mitigation technologies that reduced risk to the NASA mission. In evaluating opportunities, TEERM leveraged its knowledge of emerging contaminants and emerging technologies associated with materials obsolescence, energy demand, and contaminated sites, among others, to identify risks and evaluate risk-mitigating solutions. TEERM projects aimed to reduce cost; ensure the health and safety of people, assets, and the environment; promote efficiency; and minimize duplication. AP2 projects and successes are also documented. Most referenced documents are available on the NASA Scientific and Technical Program website (https://www.sti.nasa.gov/).

Through partnerships and using proven methods and best practices, TEERM has been successful in its mission. Key elements of the program encompassed:

- Helped project stakeholders jointly identify substitute materials and develop test protocol.
- Identified funding sources.
- Validated alternatives through laboratory or field testing.
- Transferred the data and information to end users to facilitate implementation of qualified materials at acquisition and sustainment facilities.

TEERM accomplished the following tasks:

- Monitored and reported on materials replacement projects with likely NASA applications.
- Developed risk and cost reducing projects and green technologies for handoff to other NASA programs and centers.
- Leveraged $2.4M direct and $18M indirect funding from sources outside NASA EMD since FY2005.
- Developed international relationships and collaborative projects that provided NASA ready access to SMEs and project sponsors/partners.

TEERM was successful in applying a risk-based collaborative approach to identify and evaluate technologies that could mitigate environmentally-driven risks to NASA. Recommendations for NASA and for other entities facing environmentally-driven and infrastructure risks include:

- Apply collaborative, risk-based approach to other disciplines (e.g., facility resilience), and
- Maintain relationships with outside agencies and industry.

11 References

Blanche, J., 2012. *Lead-Free Experiment in a Space Environment*. National Aeronautics and Space Administration. NASA/TM—2012–217463.

DeFranco, K., D. Lamb, D. Kleinschmidt, K Kessel and G. Morose. 2017. "Evaluation of Hexavalent Chromium Free Bond Primers for Aerospace and Defense Applications" In: *Products Finishing*. Accessed 8/27/17 at: http://www.pfonline.com/articles/evaluation-of-hexavalent-chromium-free-bond-primers-for-aerospace-and-defense-applications.

ESTCP 2003. *Non-Chromate Aluminum Pretreatments, Phase II Interim Report, Project #PP0025*. Environmental Security Technology Certification Program. Accessed 8/27/17 at: http://www.iaindy.com/Documents/ncapi.pdf.

Fields, J., F. Oteri, R, Preus and I. Baring-Gould. 2016. *Deployment of Wind Turbines in the Built Environment: Risks, Lessons, and Recommended Practices*. National Renewable Energy Laboratory, Golden, CO. NREL/TP-5000-65622.

Greene, B., 2017. *NASA and ESA Collaboration on Hexavalent Chrome Free Coatings.* National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-E-DAA-TN42261.

Griffin, C., 2009. *NASA TEERM Project: Corn Based Blast Media.* National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-2009-084.

Hill, R., 2001. *Joint Group on Pollution Prevention: Partnering for Progress*. National Aeronautics and Space Administration, Kennedy Space Center, FL. NASA ID: 20010087268.

JG-PP, 2001. "Joint Group on Pollution Prevention". Accessed 9/25/17 at: http://infohouse.p2ric.org/ref/20/19926/JG_PP/jg_pp.pdf.

Kessel, K., 2005. *Lead-Free Soldering for Space Applications, Lead-Free Solder Body of Knowledge*. NASA NEPP Program Document, Marshall Space Flight Center, Huntsville, Alabama.

Kessel, K., 2009a. *NASA-DoD Lead-Free Electronics Project.* National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-2009-116.

Kessel, K., 2009b. *Space Shuttle Program - Tin Whisker Mitigation*, National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-2009-097.

Kessel, K., 2010a. *Hypergolic Propellant Destruction Evaluation Cost Benefit Analysis.* National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-2013-12.

Kessel, K. 2010b. *NASA-DoD Lead-Free Electronics Project*. National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-2010-163.

Kessel, K., 2011a. *NASA-DoD Lead-Free Electronics Project. DRAFT Joint Test Report*. National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-2011-171R, KSC-2011-171.

Kessel, K., 2011b. *NASA-DoD Lead-Free Electronics Project.* National Aeronautics and Space Administration, Kennedy Space Center, FL. Document ID: 20110023218.

Kessel, K, 2012a. *Hexavalent Chrome Free Coatings for Electronics Applications: Joint Test Report.* National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-2012-263.

Kessel, K. 2012b. *Hex Chrome Free Coatings for Electronics (NASA-DoD)* National Aeronautics and Space Administration, Kennedy Space Center, FL KSC-2012-214.

Kessel, K., 2013. *GSDO Program Hexavalent Chrome Alternatives: Final Pretreatments Test Report.* National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-2013-284.

Kessel K. 2014. *NASA-DoD Lower Process Temperature Lead-Free Solder Project Overview.* National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-E-DAA-TN14130.

Kessel, K., 2015. *NASA and ESA Collaboration on Hexavalent Chrome Alternatives Pretreatments Only Interim Test Report.* National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-E-DAA-TN25897.

Kessel, K., 2016a. *Alternative to Nitric Acid Passivation*. National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-E-DAA-TN36078.

Kessel, K. 2016b, *Environmentally Preferred Coatings for Steel.* National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-E-DAA-TN36076.

Kessel, K. and M. Rothgeb, 2011. *NASA TEERM Hexavalent Chrome Alternatives Projects.* National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-2011-017.

Kessel, K., 2017. "Replacing Hexavalent Chromium in Pretreatments for Aerospace Applications "In: *Products Finishing.* Accessed 9/24/17 at: .http://www.pfonline.com/articles/replacing-hex-chrome-for-aerospace-applications

Klebanoff, L. and P. Devlin, 2011. " X.1 Fuel Cell Mobile Lighting". In: *DOE Hydrogen and Fuel Cells Program*, FY2011 Annual Progress Report., Department of Energy Fuel Cells Program, DOE/GO-102011-3422.

Kolody, M. R., Curran, J. P., and M.L. Calle, 2014. *A Five-year Performance Study of Low VOC Coatings over Zinc Thermal Spray for the Protection of Carbon Steel at the Kennedy Space Center.* National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-E-DAA-TN12399.

Lamb, D., 2016. "NASA TEERM Cr6+ Free Bond Primer Replacement Project". ASETS Defense 2016 Workshop. Accessed 8/27/17 at https://serdp-estcp.org/content/download/41315/394519/version/1/file/3.10-Lamb_ASETS+Defense+Bond+Primer+NASA+TEERM+Lamb+Final.pdf.

Lewis, P., 2007a. *Joint Test Report for Validation of Alternative Low-Emission Surface Preparation/Depainting Technologies for Structural Steel* National Aeronautics and Space Administration, Kennedy Space Center, FL Document ID: 20110010944.

Lewis, P. 2007b. *Joint Test Report For Validation of Alternatives to Aliphatic Isocyanate Polyurethanes*. National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-2011-085.

Lewis, P, 2007c. *Cost-Benefit Analysis for Alternatives to Aliphatic Isocyanate Polyurethanes* National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-2011-087.

Lewis, P., 2008a. QuEST: Qualifying Environmentally Sustainable Technologies.Vol.3. National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-2008-134.

Lewis, P., 2008b. *Joint Test Plan for Gas Dynamic Spray Technology Demonstration.* National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-2008-257.

Lewis, P. 2011a. *Gas Dynamic Spray Technology Demonstration Project Management. Joint Test Report* National Aeronautics and Space Administration, Kennedy Space Center, FL. Document ID: 20110014950.

Lewis, P., 2011b. *Demonstration/Validation of Environmentally-Preferable Coatings for Launch Facilities.* National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-2012-107.

Lewis, P., Kolody, M., and J. Curran, 2013a. *Alternative to Nitric Acid Passivation*, Department of Defense Corrosion Conference, 2013, Fort Meade MD. KSC-2013-280.

Lewis, P, Kolody, M. and J. Curran, 2013b. *Alternative to Nitric Acid for Passivation of Stainless Steel Alloys.* Department of Defense Corrosion Conference, 2013, Fort Meade MD. KSC-2013-281.

Lewis, P., and S. Valek. 2010. *NASA International Environmental Partnerships.* National Aeronautics and Space Administration, Kennedy Space Center, FL. Document ID: 20100040470.

McLaughlin, R., 2009. *Precision Cleaning of Oxygen Systems and Components*. NASA Kennedy Space Center, FL. Document ID: 209003241.

McLaughlin, R., 2013. *Project Profile: Hydrogen Fuel Cell Mobile Lighting Tower (HFCML)*, NASA Kennedy Space Center, FL. KSC-2013-124.

Mitchell, M. and N. Lowrey, 2015. *Replacement of Hydrochlorofluorocarbon (HCFC)-225 Solvent for Cleaning and Verification Sampling of NASA Propulsion Oxygen Systems Hardware, Ground Support Equipment and Associated Test Systems.* National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville, AL. M15-4568.

Morose, G., D. Lamb, D. Pinsky, K. DeFranco, Z. Powell and A. Manavbasi., 2013." Evaluation for Alternatives to Hexavalent Chromium Sealants". *Metal Finishing*, Vol 111, Issue 3, pp.32-37, 63.

NASA, 2006. *QuEST: Qualifying Environmentally Sustainable Technologies*. NASA Kennedy Space Center, FL. KSC-2013-245.

NASA, 2016. *2016 NASA Strategic Sustainability Performance Plan*. National Aeronautics and Space Administration, Washington. D.C.

NASA Policy Directive (NPD 8500.1), *NASA Environmental Management* National Aeronautics and Space Administration, Washington. D.C.

NASA Procedural Requirements (NPR 8750.1), *NASA Energy Management* National Aeronautics and Space Administration, Washington. D.C.

NASA Scientific and Technical Program Website (https://www.sti.nasa.gov/).

Photonics, 2017. "NASA, Norwegian Map Authority to Develop Arctic Satellite Laser Ranging Station". In: *Photonics*, 2017, accessed 9/24/17 at https://www.photonics.com/Article.aspx?AID=62467.

Rothgeb, M., 2003. *Assessment of NASA Solder Operations and Risks Associated with Lead-Free Solders.* National Aeronautics and Space Administration, Kennedy Space Center, FL.

Rothgeb, M., and R, McLaughlin, 2008. *Final Report on Portable Laser Coating Removal Systems Field Demonstrations and Testing.* National Aeronautics and Space Administration, Kennedy Space Center, FL. NASA CR-2008-214754.

Rothgeb, M. and K. Kessel, 2013. *Hexavalent Chrome Free Coatings for Electronics Applications: Joint Test Report.* National Aeronautics and Space Administration, Kennedy Space Center, FL. KSC-2013-111.

Rothgeb, M. and Kessel, K., 2015.*NASA and ESA Collaboration on Hexavalent Chrome Alternatives – Pretreatments with Primers Screening Final Test Report.* National Aeronautics and Space Administration, Kennedy Space Center, FL., Document ID: 2015014973.

ScienceDaily, 2017. "Svalbard's Electric Power Could Come from Hydrogen", ScienceDaily. Accessed 9/25/17 at: https://www.sciencedaily.com/releases/2017/02/170207104356.htm.

Starry, O., J. Lea-Cox, J. Zazanis and D. Kohanbash., 2014. "Using Scaleable Sensor Networks to Estimate Green Roof Stormwater Runoff in Remote Locations". Presented at the 2014 International Workshop on Environment and Alternative Energy, October 21, 2014.

APPENDIX A. Acronyms

ACE	Aerospace Chromium (and Cadmium) Elimination Team
AFB	Air Force Base
AFRL	Air Force Research Laboratory
AFSPC	Air Force Space Command
AIA	Aerospace Industries Association
AMC	Avionics Maintenance Conference
AMISR	Advanced Modular Incoherent Scattering Radar
ANG	Air National Guard
ANIMEE	National Association of Electric and Electronic Manufactures
AP2	Acquisition Pollution Prevention
APEX	Association Connecting Electronics Industries
APL	Approved Products List
ARINC	Aeronautical Radio, Incorporated
ARL	Army Research Laboratory
ASETSDefense	Advanced Surface Engineering Technologies for a Sustainable Defense
ATK	Alliant Techsystems
C3P	Centre for Pollution Prevention Program
CAA	Clean Air Act
CALCE	Computer Aided Life Cycle Engineering
CBA	Cost Benefit Analysis
CCAFS	Cape Canaveral Air Force Station
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CERL	Construction Engineering Research Laboratory
CFC	Chlorofluorocarbon
CFR	Code of Federal Regulations
CHP	Corn Hybrid Polymer
CNG	Compressed Natural Gas
CoF	Construction of Facilities
CPC	Corrosion Prevention and Control
CrVI	Hexavalent Chromium
CTC	Concurrent Technologies Corporation
CTG	Control Techniques Guidelines
CTIO	Coatings Technology Integration Office
CTL	Corrosion Technology Laboratory
CWA	Clean Water Act
CxP	Constellation Program
DCMA	Defense Contract Management Agency
DFARS	Defense Federal Acquisition Regulation Supplement
DfES	Design for Environment
DLA	Defense Logistics Agency
DMEA	Defense MicroElectronics Agency
DoD	Department of Defense
DOE	Department of Energy
EADS	European Aeronautic Defense and Space Company
ECOS	Sustainable Construction Practices
ECR	Environmental Compliance and Restoration

EGSE	Electrical Ground Support Equipment
EISA	Energy Independence and Security Act
ELFIPT	Industry and Government Executive Lead-Free Cooperative Integrated Process Team
ELP/FOL	El Paso Forward Operating Location
EMD	Environmental Management Division
EMEF	Railway Equipment Maintenance Company
EMI	Electromagnetic Interference
EMS	Emergency Medical Services
EO	Executive Order
EPA	Environmental Protection Agency
EPFOL	El Paso Forward Operating Location
ESA	European Space Agency
ESAC	European Space Astronomy Centre
ESTCP	Environmental Security Technology Certification Program
ESTEC	European Space Research and Technology Center
ESTEE	Earth Space Technical Ecosystem Enterprises
EU	European Union
FAA	Federal Aviation Administration
FDEP	Florida Department of Environmental Protection
FEMP	Federal Energy Management Program
FLAD	Luso-American Development Foundation
FLC	Federal Laboratory Consortium
FPL	Florida Power and Light
FY	Fiscal Year
GDS	Gas Dynamic Spray
GE	General Electric
GECI	Global Environmental Coordination Initiative
GEIA	Government Electronics and Information Technology Association
GHG	Greenhouse Gas
GPG	Green Proving Ground
GRC	Glenn Research Center
GSA	General Services Administration
GSDOP	Ground Systems Development and Operations Program
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
H_2LT	Hydrogen Fuel Cell Mobile Light Tower
HAP	Hazardous Air Pollutant
HazMat	Hazardous Materials
HCFC	Hydrochlorofluorocarbon
HFE	Hydrofluoroether
HQ	Headquarters
IHA	InoMedic Health Applications
ILTAM	Israeli Users Association of Advanced Technologies in Electronics
INASMET	International Science and Technology Center
INEGI	Institute of Science and Innovation in Mechanical and Industrial Engineering
IOMS	Infrastructure Operations and Maintenance Services
IPC	Institute for Printed Circuits
ISQ	Institute for Welding and Quality

IVD	Ion Vapor Deposited
JCAA	Joint Council on Aging Aircraft
JG-APP	Joint Group on Acquisition Pollution Prevention
JG-PP	Joint Group on Pollution Prevention
JPL	Jet Propulsion Laboratory
JRC	Joint Research Centre
JSC	Johnson Space Center
JTP	Joint Test Protocol
JTR	Joint Test Report
KSAT	Kongsberg Satellite Services
KSC	Kennedy Space Center
KSCVC	Kennedy Space Center Visitor Complex
L3	L3 Technologies
LANL	Los Alamos National Laboratory
LEADOUT	Low Cost Lead-Free Soldering Technology to Improve Competitiveness of European SME
LEAP	Lead-Free Electronics in Aerospace Project
LED	Light Emitting Diode
LEED	Leadership in Energy and Environmental Design
LLNL	Lawrence Livermore National Laboratory
MAF	Michoud Assembly Facility
MDA	Missile Defense Agency
MEK	Methyl Ethyl Ketone
MIPR	Military Interdepartmental Procurement Request
MOA	Memorandum of Agreement
MOU	Memorandum of Understanding
MSFC	Marshall Space Flight Center
NAAQS	National Ambient Air Quality Standards
NASA	National Aeronautics and Space Administration
NAVAIR	U.S. Navy Air Systems Command
NAVFAC	Naval Facilities Engineering Command
NAVSEA	Naval Sea Systems Command
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
Nd: YAG	Neodymium: Yttrium-Aluminum-Garnet
NDCEE	National Defense Center for Energy and Environment
NEN	Near Earth Network
NEPP	NASA Electronics Parts and Packaging
NESHAP	National Emissions Standards for Hazardous Air Pollutants
NIST	National Institute of Standards and Technology
NJIT	New Jersey Institute of Technology
NPD	NASA Policy Directive
NPR	NASA Procedural Requirement
NRC	Nuclear Regulatory Commission
NREL	National Renewable Energy Laboratory
NSC	Norwegian Space Agency
NSPS	New Source Performance Standards
NTRS	NASA Technical Support Server
NVR	Non-Volatile Residue
ODS	Ozone Depleting Substance

OEM	Original Equipment Manufacturer
OGMA	Aeronautical Industry of Portugal
ONRG	Office of Naval Research Global
ONRIFO	Office of Naval Research International Field Office
OSHA	Occupational Safety and Health Administration
P2	Pollution Prevention
PAFB	Patrick Air Force Base
PAR	Potential Alternatives Report
PEL	Permissible Exposure Limit
PEM	Proton Exchange Membrane
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonic acid
PFRR	Poker Flat Research Range
PLCRS	Portable Laser Coating Removal System
PPOA	Pollution Prevention Opportunity Assessment
PPONA	Pollution Prevention Opportunity Needs Assessment
PTH	Plated Through Hole
PV	Photovoltaic
PWB	Printed Wiring Board
QuEST	Qualifying Environmentally Sustainable Technologies
R&D	Research and Development
RCRA	Resource Conservation and Recovery Act
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RFI	Radio Frequency Interference
RoHS	Restriction of Hazardous Substances
RRAC	Regulatory Risk Analysis and Communication
RSA	Recycling and Sustainable Acquisition
SAA	Space Act Agreement
SBM	Spent Blast Media
SEA	Shuttle Environmental Assurance
SERDP	Strategic Environmental Research and Development Program
SLS	Space Launch System
SME	Subject Matter Expert
SMT	Surface Mount Technology
SMTA	Surface Mount Technology Association
SNL	Sandia National Laboratories
SNUR	Significant New Use Rule
SRB	Solid Rocket Booster
SRT2	Shuttle Replacement Technology Team
SSC	Stennis Space Center
SSP	Space Shuttle Program
STD	Standard
STS	Space Transportation System
SvalSat	Svalbard Satellite Station
TCA	Trichloroethane
TCE	Trichloroethylene
TEERM	Technology Evaluation for Environmental Risk Mitigation
TRL	Technology Readiness Level

TrollSat	Troll Satellite Station
TSC	Thermal Spray Coating
TSCA	Toxic Substances Control Act
TWI	The Welding Institute
U.K.	United Kingdom
U.S.	United States
UAF	University of Alaska Fairbanks
UCSD	University of California San Diego
UDRI	University of Dayton Research Institute
ULA	United Launch Alliance
UMCP	University of Maryland in College Park
USA	United Space Alliance
USAF	United States Air Force
UTC	United Technologies
VAFB	Vandenberg Air Force Base
VOC	Volatile Organic Compound
WEEE	Waste Electrical and Electronic Equipment
WFF	Wallops Flight Facility
WPAFB	Wright-Patterson Air Force Base
WSTF	White Sands Test Facility

APPENDIX B. Technology Evaluation for Environmental Risk Mitigation Projects, Stakeholders, and Sections in Compendium Report

Project Name	Year Start	Year End	Representative Stakeholders	Outside Support	Compendium Report Section
Alternatives to Hexavalent Chromium-Containing BR-127 Bond Primer	2014	2017	NASA, Raytheon (Lead), Boeing, Bombardier, GE Aviation, Harris, Lockheed Martin, NAVAIR, Northrop Grumman, Piper, Pratt & Whitney, Sikorsky, Textron Aviation, University of Massachusetts Lowell, United Technologies (UTC) Aerospace, Triumph	In-kind by consortium members	7.4.1
Alternatives to High-VOC Chrome Coatings for Aircraft Exteriors	2004	2007	NASA, C3P, TAP, OGMA	In-kind by Portuguese partners	7.4.1
Alternative to Nitric Acid Passivation Ground Systems Development and Operations Program	2009	2015	NASA (KSC, MSFC, JSC, WFF, WSTF), Air Force, Navy, USMC, Army, DLA, ESA	GSDOP, other partners in-kind	7.1.2
Building Mounted Wind Turbine Study	2014	2016	NASA JSC, DOE HQ, NREL	NREL in-kind	8.1.1
Concentrated Solar Air Conditioning for Buildings	2009	2015	NASA (JSC, WSTF, KSC), NAVFAC, Sopogy TESS/Enovity, Davis-Monthan AFB, ESTCP	ESTCP, other partners in-kind	Not Applicable (NA)
Corn Hybrid Polymer Radome Coating Removal	2005	2007	NASA, JG-PP, Navy (lead), USAF (Robins AFB)	DoD	7.3.2
CCAFS Depainting and Surface Preparation Pollution Prevention Opportunity Assessment	2005	2006	NASA, USAF (AFSPC, CCAFS, 45th Space Wing)	AFSPC	7.1.1
Environmentally Preferable Launch Coatings Ground Systems Development and Operations Program	2011	2016	NASA (KSC, SSC, WFF, WSTF), AFSPC	GSDOP, other partners in-kind	7.4.2
Evaluation and Transition of Non-Chromated Primers	2011	2015	ESTCP, NAVAIR, NASA (KSC, WFF)	ESTCP, NAVAIR	7.4.1
Evaluation for Alternatives to Hexavalent Chromium Sealants	2012	2015	NASA KSC, Raytheon, Boeing, Lockheed Martin, Northrop Grumman, University of Massachusetts Lowell	NA	7.4.1
Gas Dynamic Spray Technology Demonstration	2007	2011	NASA KSC, USAF (45th Space Wing, AFSPC, CCAFS)	AFSPC, other partners in-kind	7.4.3
Green Roof Water Management at JSC	2014	2016	NASA JSC, NREL, Portland State University, University of Maryland, Carnegie Mellon University	NREL provided instrumentation, other partners in-kind	8.3.1

Project Name	Year Start	Year End	Representative Stakeholders	Outside Support	Compendium Report Section
Hexavalent Chrome Alternatives Ground Systems Development and Operations (GSDO) Program (Hex Chrome Free Coatings for Launch Pads)	2011	2015	NASA KSC, Raytheon	GSDOP, other partners in-kind	7.4.1
Hexavalent Chrome Free Coating Systems for Aerospace (Phase 2)	2008	2012	NASA (KSC, MSFC, JSC, MAF), Hill AFB, Spirit AeroSystems, Boeing, Lockheed Martin, Raytheon, USA, ATK, ESA	In-kind	7.4.1
Hexavalent Chrome Free Coatings for Electronics	2010	2013	NASA (KSC, JSC, MSFC), NAVY, USAF, ARMY, MDA, DMEA, USA, ATK, Lockheed Martin, Harris, Raytheon, Rockwell Collins, BAE Systems, Honeywell, Boeing	In-kind	7.4.1
Hydrazines Waste Generation Review	2011	2012	NASA (KSC, WSTF, WFF), USAF (AFSPC, CCAFS, Vandenberg AFB (VAFB)	AFSPC	NA
Hypergolic Fuel Destruction Evaluation	2009	2010	NASA [KSC, MSFC/ Regulatory Risk Analysis and Communication (RRAC)], USAF (AFSPC, AFRL, CCAFS, VAFB), Cha Corp.	AFSPC	NA
Isocyanate Urethane Replacements on Structural Steel (Aliphatic Isocyanate Polyurethanes Replacement on Structural Steel)	2003	2007	NASA (KSC, SSC), AFSPC, JG-PP	In-kind	7.4.4
KSC Hydrogen Fuel Cell Mobile Lighting	2011	2012	NASA KSC, SNL, Multiquip, Altergy, Luxim, Straylight	In-kind	8.2
Laser Coating Removal for Ground Support Equipment	2005	2009	NASA (KSC, GRC, SSC), Boeing, USA, AFRL	In kind	7.5.2
Laser Coating Removal for Shuttle	2005	2008	NASA (KSC, JSC, SSPUSA, USAF (WPAFB)	In-kind	7.5.2
Launch Coatings Demonstration/Validation Phase 3	2008	2009	NASA KSC, USAF (45th Space Wing, AFSPC, AFRL/UDRI)	In-kind	7.4.2
Launch Vehicle (Rocket Motor/Payload) Processing Pollution Prevention Opportunity Assessment at Cape Canaveral Air Force Station	2006	2008	NASA KSC, USAF (AFSPC, CCAFS)	In-kind	NA
Lead-Free Solder Body of Knowledge	2005	2005	NASA MSFC/NEEP	In-kind	7.6.1

Project Name	Year Start	Year End	Representative Stakeholders	Outside Support	Compendium Report Section
Lead-Free Solder Testing for High Reliability Electronics (1st TEERM Lead-Free Solder Project)	2001	2006	NASA (KSC, JPL, MSFC, JSC, GSFC, ARC, USA-SRB, Boeing-Orbiter), JG-PP, USAF, Army, Navy, Marines, DOE, and more than 25 major companies from Defense and Space Industry	In-kind	7.6.1
Lead-Free Technology Experiment in a Space Environment (Lead-Free Electronics Demo in Space)	2008	2011	NASA MSFC	NA	7.6.1
Life-Cycle Corrosion of Space Vehicles	2008	2012	NASA (KSC, MSFC), USAF Coatings Technology Integration Office (CTIO, UDRI, AFSPC), ATK	In-kind	NA
Low/No-VOC and Nonchromate Coating System for Support Equipment	1999	2003	NASA KSC, CCAFS, JG-PP, other DoD	NA	7.4.1
Low-Temperature Cure (Ultraviolet Light) Powder Coatings	2008	2011	NASA (KSC, Orbiter (Boeing), USAF, Navy, DOE, JG-PP, ESTCP	ESTCP	NA
Low VOC Coatings and Depainting Technologies Field Testing Phase 2	2006	2009	NASA (KSC, SSC), USAF (45th Space Wing, AFSPC, CCAFS, VAFB)	AFSPC	7.4.5
Low-Emission Depainting on Steel	2003	2006	NASA (KSC, SSC, GRC), AFSPC	In-kind	7.4.5
Lower Process Temperature Lead-Free solders	2012	2016	NASA, many major departments and contractors from Defense and Space Industry	In-kind	7.6.1
Low-VOC Identification Marking	1998	2003	NASA, ESTCP, JG-PP	ESTCP	NA
Membrane Removal of VOCs Project 1	2001	2002	NASA, NJIT, Chembrane, AMT	NA	NA
Membrane Removal of VOCs Project 2	2006	2009	NASA (KSC, WFF, MSFC, GRC, Plumbrook, MAF, WSTF, JPL, NASA Clean Air WG), NJIT, Chembrane, AMT, C3P	Chembrane	7.2.1
NASA/ESA Verification of Hexavalent Chromium Free Coatings	2011	2018	NASA KSC, ESA, Navy	ESA & Navy in-kind	7.4.1
NASA/ESA Collaboration on Environmentally-preferable Coatings for Launch Facilities	2015	2017	NASA (WFF, SSC, KSC), ESA	In-kind	7.4.2
NASA and C3P Collaboration on Sustainable Construction Practices (ECOS)	2011	2012	NASA, C3P	NA	8.3.2

Project Name	Year Start	Year End	Representative Stakeholders	Outside Support	Compendium Report Section
NASA-DoD Lead-Free Electronics Project (Lead-Free Electronics for Rework) (2nd TEERM Lead-Free Project)	2006	2011	NASA, many major departments and contractors from Defense and Space Industry	In-kind	7.6.1
NASA Evaluation of Corn Based Alternative to Plastic Media Blasting for Aerospace Applications	2011	2012	NASA (JSC, KSC, JSC), ADM, MidVale, USA, Shuttle Program	In-kind	7.3.2
NASA Evaluation of Spent Blast Media as an Alternative Aggregate in Concrete Applications	2012	2014	NASA (KSC, WFF, MSFC), Advantage Concrete, Hanson, USAF, University of Florida	In-kind	7.3.1
Non-Chrome Aluminum Pretreatments	2000	2006	NASA, USA, ESTCP, JG-PP	ESTCP, In-kind	7.4.1
Non-Chrome Primers for Aircraft Exteriors	1995	2003	NASA, ESTCP, JG-PP, Boeing	ESTCP, In-kind	7.4.1
Non-Chrome Primer on Orbiter Columbia (extension of Non-Chrome primer for aircraft exterior	1995	2003	NASA, SSP, JG-PP, Boeing	In kind	7.4.1
Non-Chrome Coating Systems for Aerospace (Phase 1)	2005	2009	NASA (KSC, MSFC, JSC, SEA), Boeing, USA, USAF (Hill AFB, WPAFB/AFRL)	AFSPC, In-kind	7.4.1
Precision Cleaning of Oxygen Systems and Components	2007	2009	NASA WSTF, Yale University	NA	7.5.3
Non-ODC Oxygen Line Cleaning for use on DOD Weapons Systems	1999	2003	NASA WSTF, ESTCP, JG-PP, USAF (Tinker AFB, Robins AFB, Oklahoma Air National Guard (ANG), Tulsa ANG, and the B-1B, B-2, F-15, and F-16 aircraft programs)	ESTCP	7.5.3
Parts Washers	2004	2005	NASA centers, Rochester Institute of Technology	Vendors, Rochester Institute of Technology	7.5.1
Poker Flat Research Range	2015	2017	NASA (PFRR, WFFUAF, ABB)	WFF	8.1.2
Portable Laser Coating Removal	2001	2005	NASA, JG-PP, ESTCP	ESTCP	7.5.2
PPONAs at NASA Centers	2000	2004	NASA centers	NA	7.1.1
PPONAs in Portugal	2003	2003	NASA, C3P, ISQ, INEGI	C3P	7.1.1
Solder Assessment Study	2002	2003	NASA	NA	7.6.1
SvalSat Svalbard Renewable Energy Assessment	2015	2016	NASA, ESA, KSAT, NSC, Space Norway	In-kind	8.1.3

APPENDIX C. Technology Evaluation for Environmental Risk Mitigation Milestones

Year	Milestone
1998	• NASA establishes AP2
1999	• First NASA PPOA (KSC) begins
2000	• SEA established
2002	• NASA signs Joint Statement with Portuguese Ministry of Environment to collaborate on P2 • C3P created • AP2 and C3P initiated workshop in London focused on lead-free solder
2003	• First C3P and NASA Technical Workshop in Portugal "Integrating Common Problems for Shared Solutions" • Protocol Signing Ceremony – Cooperation and Technical Exchange Agreements signed among C3P and OGMA, TAP-Air Portugal, ANIMEE, the National Association of Electric and Electronic Manufacturers, Caetano Bus (car/bus manufacturers), and British Aerospace Systems
2004	• AP2's first collaborative effort with AFSPC – Isocyanate-free coatings project • AP2's first project funded by AFSPC – "CCAFS Depainting and Surface Preparation PPOA" • First collaborative effort with C3P, TAP, and OGMA to target reduction of Crave, Cadmium, and VOCs in aircraft maintenance operations
2007	• AP2 renamed TEERM • NASA assumed JG-PP chairmanship for next two years • TEERM's first project where environmentally-preferable coatings were first applied to a launch pad – the "Low VOC Coatings and Depainting Technologies Field Testing" Phase II
2008	• First TEERM project to evaluate thermal spray technologies for repairing coatings on launch complexes and GSE – GDS project • USAF recognized TEERM's lead-free projects in its March 31 Airworthiness Advisory
2009	• Coordinated a field demonstration of low VOC coatings at CCAFS Launch Complex 17 • First TEERM project evaluating entire coatings systems that contain no CrVI – "Hexavalent Chrome-Free Coating Systems" project • C3P was awarded Government funding to begin working with Portugal municipalities to increase the energy efficiency of buildings using renewable energies and sustainable construction • Transitioned the chairmanship of JG-PP from NASA to U.S. Army
2010	• TEERM engaged technical representatives from NASA, DOD, and ESA in beginning development and requirements definition for a new project and first-ever TEERM collaborative effort with ESA targeting alternatives to CrVI for electronics and avionics. • First TEERM project to receive funding from ESTCP – "Concentrated Solar Air Conditioning for Buildings" project. Concept of project was developed and proposed by TEERM • TEERM's first site visit to JSC's EPFOL resulting in technology demonstration, equipment upgrades, and process improvement identification • TEERM presented on its Lead-Free Electronics Project at the 13th DOD/NASA/FAA Aircraft Airworthiness and Sustainment Conference in Austin, TX • TEERM hosted a face-to-face meeting of Government and industry representatives interested in CrVI-free coatings for electronics at KSC • First student poster/presentation session at a NASA international environment and energy workshop

Year	Milestone
2011	• First TEERM technology demonstration/validation with DOE (Hydrogen fuel cell lighting tower demonstration at KSC) • NASA GSDOP awards funding to three environmental projects proposed and managed by TEERM: Validation of Alternative to Nitric Acid Passivation; Environmentally Preferable Launch Coatings; and CrVI Coatings • TEERM visited four ECOS project municipalities in Portugal (Beja, Moura, Torres Vedras, and Peniche) supporting the NASA-C3P International Agreement • New, compliant TEERM website launched • TEERM delivered presentation on the Fuel Cell Mobile Light Project at the Advances in Hydrogen Energy Technologies 4th International Seminar in Viana do Castelo, Portugal • Began joint project with NAVAIR to test new coating system on NASA aircraft
2012	• MOA between NASA HQ and KSC to continue TEERM • Implemented SBM in concrete at KSC Propellants North first TEERM project to be fully funded using KSC sustainability funds • Two presentations on TEERM were made at a NASA seminar, *Introduction to Green Engineering*, at KSC
2013	• TEERM negotiated and secured backup fuel cells from DOE/Army Construction Engineering Research Laboratory for use at KSC • Installation of solar PV facility funded by FPL at KSCVC. Opportunity was initiated and supported by TEERM • TEERM idea for a microgrid planning study at NASA WSTF (to be performed by SNL and Army CERL) for critical energy infrastructure was accepted by NASA • Consultant studies began to evaluate bus fleet alternatives, notably Compressed Natural Gas (CNG) and CNG fueling, for the KSCVC • TEERM secured NREL/DOE funding for instrumentation of JSC Bldg.12 green roof and coordinated university data analysis for storm water management • TEERM coordinated NREL funded collaboration with NASA on JSC Bldg. 12 wind field studies including necessary instrumentation hardware and installation
2014	• NREL funded wind and green roof instruments and installation under an Interagency Agreement signed January 14, 2014 • PERM Meeting at KSC, February 11-13, 2014 • Attended ESA Materials & Processes meetings at ESTEC, Noordwijk, The Netherlands, April 2014 • Acquired low-mileage hydrogen fuel cell electric bus from DOE-SNL • ESA Sustainability Roundtable with regional member states, Lisbon, Portugal, May 2014 • ESA Sustainability Roundtable in Stockholm, Sweden, December 2014
2015	• Svalbard, Norway meetings, May-June 2015 • Attended ESA Materials & Processes meetings at ESTEC, September 2015
2016	• Army Tank-automotive & Armaments Command Meeting at Saturn V Facility at KSC, April 19-21, 2016 • TEERM established project stakeholders within SLS to support the continuation of the NASA/ESA Hexavalent Chrome Free Coatings project. The test plan was modified to specifically meet SLS requirements, ensuring that data from the project will be valuable to the program. • TEERM begins regular involvement in two non-NASA government groups: GPG Interagency Technology Coordination; and Corrosion Technology Interchange Meetings
2017	• Core TEERM task order ends September 30, 2017. End date for TEERM MOA between NASA HQ and KSC.

APPENDIX D. Technology Evaluation for Environmental Risk Mitigation Partners

Partner Name	Country of Residence	Organization Type	Primary Role in TEERM Activity
AMT	U.S.	Industry	Vendor
ATK	U.S.	Industry	Multiple projects
BAE Systems	U.K.	Industry	Technical representative
BAE Systems	U.S.	Industry	Testing partner and SME
Boeing	U.S.	Industry	Testing partner and SME
Celestica	Canada	Industry	Testing partner
Hanson Slag Cement	U.S.	Industry	Vendor
C3P	Portugal	NGO	Technical representative, Workshop support
Cha Corp.	U.S.	Industry	Technology manufacturer
Chembrane	U.S.	Industry	Vendor
COM DEV	Canada	Industry	Testing partner
Concurrent Technologies Corporation (CTC)	U.S.	Industry	Testing partner
COR-RAY Painting Company	U.S.	Industry	Testing partner and SME
DLA	U.S.	Government DLA/DOD	SME
DMEA	U.S.	Government DMEA/DOD	Project funding
ESA	The Netherlands	Government	Multiple projects, funding, Workshop support
General Dynamics	U.S.	Industry	Testing partner
GE	U.S.	Industry	SME
Harris	U.S.	Industry	SME
Honeywell	U.S.	Industry	SME
ISQ	Portugal	Industry	Multiple projects
JG-PP	U.S.	Government	Multiple projects, Testing partner
Joint Research Centre (JRC)	The Netherlands	Government European Commission	Testing partner and SME
Lockheed Martin	U.S.	Industry	Testing partner and SME
Midvale Technologies	U.S.	Industry	Evaluation of Corn-Based Alternative to Plastic Blast Media in Aerospace Applications
Missile Defense Agency (MDA)	U.S.	Government MDA/DOD	SME
NASA Ames Research Center	U.S.	Government NASA	SME
NASA Dryden Flight Research Center	U.S.	Government NASA	SME

Partner Name	Country of Residence	Organization Type	Primary Role in TEERM Activity
NASA GRC	U.S.	Government NASA	Testing partner
NASA GSFC includes NEPP	U.S.	Government NASA	SME
NASA JPL	U.S.	Government NASA	SME
NASA JSC	U.S.	Government NASA	Multiple projects
NASA KSC Includes Corrosion Laboratory	U.S.	Government NASA	Multiple projects
NASA Langley Research Center	U.S.	Government NASA	SME
NASA MAF	U.S.	Government NASA	Multiple projects
NASA MSFC	U.S.	Government NASA	Multiple projects, SME
NASA Santa Susana Field Laboratory	U.S.	Government NASA	SME
NASA SSC	U.S.	Government NASA	Multiple projects, SME
NASA Principal Center for RSA	U.S.	Government NASA	Multiple projects, funding
NASA RRAC Principal Center	U.S.	Government NASA	Identifies current and future risks to mission. Project and technology advocacy
NASA WFF	U.S.	Government NASA	Testing partner and SME
NASA WSTF	U.S.	Government NASA	Testing partner and SME
NIST	U.S.	Government NASA	Testing partner and SME
NREL	U.S.	Government NASA	Testing partner and SME
NJIT	U.S.	Academia	Testing partner and SME
Nihon Superior	Japan	Industry	Material Supplier and Failure Analysis Lab
Northrop Grumman	U.S.	Industry	SME
Oak Ridge National Labs	U.S.	Government DOE	ORNL Prototype Groundwater Monitor
OGMA	Portugal	Industry	Stakeholder
Portland State University	U.S.	Academia	Testing partner and SME
Ranger Construction	U.S.	Industry	Vendor
Raytheon	U.S.	Industry	Testing partner and SME
Rockwell Collins	U.S.	Industry	Testing partner and SME

Partner Name	Country of Residence	Organization Type	Primary Role in TEERM Activity
Rochester Institute of Technology	U.S.	Academia	Testing partner and SME
SNL	U.S.	Government and Industry DOE	Testing partner and SME
SEA Initiative	U.S.	Government and Industry (contractor) NASA	Multiple projects, SMEs
Sopogy	U.S.	Industry	Technology manufacturer
Space Coast Launch Services	U.S.	Industry	Testing partner and SME
Spirit Aerospace	U.S.	Industry	SME
TAP Air	Portugal	Industry	Testing partner
TESS	U.S.	Industry	SME and data modeler
USAF **including AFSPC PAFB, VAFB, Davis-Monahan AFB, etc.**	U.S.	Government DOD	Multiple projects
U.S. Army	U.S.	Government DOD	SME
U.S. Marine Corps	U.S.	Government DOD	SME
U.S. Navy **including NAVAIR, Naval Sea Systems Command (NAVSEA), NAVFAC, etc.**	U.S.	Government DOD	Multiple projects
United Launch Alliance (ULA)	U.S.	Industry	Testing partner and SME
USA	U.S.	Industry	Evaluation of Corn Based Alternative to Plastic Blast Media in Aerospace Applications
United Technologies Research Center	U.S.	Industry	SME
UDRI	U.S.	Industry	Testing partner and SME
University of Alaska	U.S.	Academia	Testing partner and SME
University of Central Florida	U.S.	Academia	Testing partner and SME
University of Florida	U.S.	Academia	Testing partner and SME
University of Maryland	U.S.	Academia	Testing partner and SME
University of Mass Lowell	U.S.	Academia	Testing partner and SME
Yale University	U.S.	Academia	SME

APPENDIX E. Military Interdepartmental Procurement Request Funding

Project	Fiscal Year	MIPR Organization
NASA/CCAFS Low VOC Coatings and Depainting	2007	HQ AFSPC
CCAFS PPONA Launch Vehicle Processing	2007	HQ AFSPC
Gas Dynamic Spray	2007	HQ AFSPC
Vibration Testing of Lead-Free Solders	2008	DMEA
Hypergolic Fuel Destruct Evaluation Task	2008	HQ AFSPC
Hypergolic Fuel Destruct Evaluation Task Phase II	2010	HQ AFSPC
Concentrated Solar Air Conditioning for Buildings	2010	ESTCP
Concentrated Solar Air Conditioning for Buildings	2011	ESTCP
TEERM Hex Chrome Coatings for Electronics	2011	Navy
Hydrazine Waste Generative Review	2011	HQ AFSPC
Comprehensive Evaluation and Transition of Non-Chromated Paint Primers	2011	ESTCP
GSDOP Alternative to Nitric Acid Passivation	2011	GSDOP
GSDOP Environmentally-Preferable Launch Coatings	2011	GSDOP
GSDOP Hexavalent Chrome-Free Coatings	2011	GSDOP
UDRI Eastern Range Coatings Support	2012	AFSPC
Concentrated Solar Air Conditioning for Buildings	2012	ESTCP
Hexavalent Chrome-Free Coatings for Electronics Applications	2012	ESTCP
Comprehensive Evaluation and Transition of Non-Chromated Paint Primers	2013	ESTCP
Concentrated Solar Air Conditioning for Buildings	2013	ESTCP
Comprehensive Evaluation and Transition of Non-Chromated Paint Primers	2014	ESTCP
Comprehensive Evaluation and Transition of Non-Chromated Paint Primers	2015	ESTCP
Concentrated Solar Air Conditioning for Buildings	2015	ESTCP
GSDOP Alternative to Nitric Acid Passivation	2015	GSDOP
GSDOP Environmentally-Preferable Launch Coatings	2015	GSDOP
GSDOP Hexavalent Chrome-Free Coatings	2015	GSDOP
Comprehensive Evaluation and Transition of Non-Chromated Paint Primers	2016	ESTCP

APPENDIX F. Technology Evaluation for Environmental Risk Mitigation Participation in Technology Forums

Technology Forums	Purpose	Lead Organization and Participants
GPG Interagency Technology Coordination	GSA GPG Program leverages GSA's real estate portfolio to evaluate innovative technologies that accelerate GSAs sustainability goals, reduce operational costs, and lead market transformation.	Lead: GSA DOE TEERM
Corrosion Technology Interchange Meetings	Discuss projects addressing CrVI replacements in pretreatments and primers.	Lead: Army Research Lab NAVAIR Marine Corps KSC CTL TEERM
Space Coast Interagency Environmental Partnership	Alliance cemented in the 2000s continues to help Florida Department of Environmental Protection (FDEP) work with strategic partners along the Space Coast to better protect the state's environment. The consortium meets to discuss environmental concerns that may impact Space Coast military and federal agencies.	Lead: Rotating) FDEP PAFB CCAFS NASA and DoD Contractors TEERM
Precision Cleaning and Contamination Control	Agency-wide group focused on addressing precision cleaning solvent replacement issues.	Lead: WSTF NASA Centers TEERM
Aerospace Chromium (and Cadmium) Elimination (ACE) Team	ACE team shares OEM successes/failures at minimizing and eliminating CrVI and cadmium.	Lead: Raytheon Aerospace/ Defense OEMs (Boeing, Lockheed Martin, N-Grumman, UTC, Pratt-W, Sikorsky) DoD [NAVAIR, Aviation and Missile Command (AMCOM) G4, Army Research Laboratory (ARL), AFRL] TEERM
Advanced Surface Engineering Technologies for a Sustainable Defense (ASETSDefense)	Forum and resource for information, tools, DoD policy, and assistance on sustainable surface engineering and other clean alternatives.	Lead: Office of Under-Secretary of Defense for Environment [ESTCP/ Strategic Environmental Research and Development Program (SERDP)] Aerospace/ Defense OEMs, DoD TEERM
ESA Materials and Processes Industry Working Group	Forum of ESA and ESA industry partners to discuss ongoing efforts to find replacements for REACH restricted or "at risk" of obsolescence materials used on spacecraft and supporting equipment and infrastructure.	Lead: ESA European Aeronautic Defense and Space Company (EADS) Astrium Other aerospace contractors TEERM

Technology Forums	Purpose	Lead Organization and Participants
KSC Environmental Solutions Partnership	Ensure access to space while protecting the public health and environment: • Raise Awareness • Promote Communication • Promote P2 • Share Information/Best Practices • Examine Alternatives • Encourage Recycling and Acquisition of Environmentally Preferable Products and Services • Identify Environmental Technologies and Validate Through Joint Activities	Lead: KSC Environmental Branch Abacus Corporation, Information Management Communication Services Air Force 45 Civil Engineer Squadron (CES)/CEAN ATK Boeing Brevard County Solid Waste DNC Parks and Resorts at KSC, Inc. Exelis Inc. and L3 Communications FDEP InDyne, Inc. [Infrastructure Operations and Maintenance Services (IOMS) contact] InoMedic Health Applications (IHA) ITB Jacobs Technology Lockheed Martin Space Florida SpaceX ULA Vencore VZ Technology URS Corporation TEERM
Lead-free Solder Environmental Risk Mitigation Team (PERM)	Forum to discuss ways to reduce electronics reliability risk resulting from global movement toward lead-free solder alloys and surface finishes.	Lead: Air Force Army, Navy, Marine Corp, DLA, Aerospace and defense contractors NASA EEE Parts Program at GSFC TEERM
Industry-Government Non-Cr Bond Primer Team	To identify potential alternatives for hex-chrome based bond primers and brief team members on progress toward alternatives qualification.	Lead: Boeing Suppliers (including Cytec and 3M), Aerospace/ Defense OEMs (including Raytheon) DoD TEERM
JG-PP Working Group	Advocate and facilitate across JG-PP members and industry, methodologies / processes / materials that reduce environmental and health impact across weapon / space systems integrated life cycle management to reduce risk to missions.	Lead: Tri-service (Rotating lead) Army, Navy, Marine Corp, Air Force, DLA NASA HQ-EMD SEA TEERM

Technology Forums	Purpose	Lead Organization and Participants
Hydrogen Sensor Task Group Meeting	Discuss hydrogen sensor research in U.S. and Europe; and updates on the Hydrogen Sensors Standards subgroup.	Lead: NREL Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL) Industry (Air Products and Chemicals, H2Scan Corporation, California Fuel Cell Partnership, Nuclear Regulatory Commission (NRC), Nextech, Hydrogenics) GRC, WSTF TEERM
Joint Service Solvent Substitution Working Group	Exchange solvent substitution information among DoD Services and NASA, as well as provide status and recommendations pertaining to projects and implementation efforts, while identifying and discussing potential future research and development opportunities.	Navy Army Marine Corp, Air Force, DLA NASA Precision Cleaning and Contamination Control TEERM
AIA Chemicals Subcommittee (formerly REACH Working Group)	Responsible for coordinating activities related to REACH. Technical reviews included: - CrVI - Cadmium - Phthalates - Decabromodiphenyl ether (deca-BDE) - Perfluorooctanoic Acid (PFOA) - Perfluorooctanesulfonic acid (PFOS)	Lead: AIS Aerospace/ Defense OEMs DoD TEERM