Environmentally-driven Materials Obsolescence: Material Replacements and Lessons Learned from NASA's Space Shuttle Program

October 24, 2013
ESRIN, Frascati, Italy
2013 International Workshop on Environment and Alternative Energy

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Outline

• Space Shuttle Overview
• Montreal Protocol and Later Regulatory Challenges
• Space Shuttle Approach to Mitigation
• Space Shuttle Environmentally-driven Materials Obsolescence Risks
• Major Mitigation Actions
• Space Launch System and Future Risks
• Lessons Learned
NASA Space Shuttle Program (SSP)
Operations 1981-2011
NASA Space Shuttle Elements

- Orbiter – Re-useable Spacecraft
- Space Shuttle Main Engines (SSME, LOX/LOH fueled)
- External Tank (ET) – Cryogenic LOX/LOH tanks for SSMEs
- Solid Rocket Boosters/Motors (SRB, RSRM) – ammonium perchlorate solid propellant
- Ground Support Equipment (GSE)
Montreal Protocol 1987

- First big environmental driver of materials obsolescence.
- Class I Ozone Depleting Substances (ODS) phased out included chlorofluorocarbons (CFCs) and 1,1,1 trichloroethane (TCA).
- CFCs were used in many Shuttle operations including CFC-113 for precision cleaning and CFC-11 as a blowing agent in polyurethane foam.
- TCA was used in critical bonding applications during Orbiter processing, RSRM manufacturing operations, and SRB bonding operations and coatings.
Later Challenges

• Direct regulation or restriction increased in the U.S.
• U.S. National Environmental Standards for Hazardous Air Pollutants (NESHAPS)
• Criteria Pollutant Regulations: Volatile Organic Carbon (VOCs)
• Occupational Safety and Health Administration restrictive standards for chromium, cadmium and lead
• New European regulations that could affect availability of critical materials
• New European regulations that could impact additives to materials, reformulations, increased uncertainty
Space Shuttle Program Approach to Environmentally-driven Materials Obsolescence

• In response to the Montreal Protocol, Materials and Processes (M&P) representatives began to meet informally
• NASA and the SSP established teams of subject matter experts.
• In 2000, the SSP chartered the Shuttle Environmental Assurance (SEA) Initiative.
• SEA worked closely with the Regulatory Risk Analysis and Communication Principal Center (RRAC) to identify emerging and changing regulations that could affect SSP operations.
• SEA used a continuous risk management approach to identify, analyze, mitigate, and track environmentally driven materials obsolescence issues.
• Mitigation approaches included:
  – regulatory mitigations
  – qualification of reformulated materials
  – replacement of materials
  – changes in the process to be able to delete materials
  – stockpiling
• Some risks, especially near the end of the SSP, were tracked or accepted.
• Coordinated proactive effort involving NASA HQ, Regulatory team, Materials and Process Engineers, Program Elements and Prime Contractors.
# Regulatory Drivers and Shuttle Materials Impacts

<table>
<thead>
<tr>
<th>Requirement/Regulation</th>
<th>Material Affected</th>
<th>SSP Impacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protection of Stratospheric Ozone Montreal Protocol; CAA, Title VI</td>
<td>Class I ODS: CFCs, Freon®</td>
<td>Precision cleaning; blowing agent</td>
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<tr>
<td></td>
<td>Class I ODS: Halon</td>
<td>Fire protection: Orbiter and GSE</td>
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<tr>
<td></td>
<td>Class I ODS: TCA</td>
<td>Cleaning operations RSRM and Orbiter</td>
</tr>
<tr>
<td>Protection of Stratospheric Ozone Montreal Protocol; CAA, Title VI</td>
<td>Class II ODS: HCFC 141b</td>
<td>Thermal Protection System (TPS): ET, RSRM, RSRB, Orbiter</td>
</tr>
<tr>
<td>NESHAPs CAA, Title III</td>
<td>HAPs</td>
<td>Surface cleaning coating, and associated operations</td>
</tr>
<tr>
<td>Criteria Pollutant Regulations CAA, Title I</td>
<td>VOCs</td>
<td>Surface cleaning coating, and associated operations</td>
</tr>
<tr>
<td>National Ambient Air Quality Standards: NAAQS for Ozone</td>
<td>ozone</td>
<td>Potential increased restrictions on VOC emissions</td>
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<tr>
<td>Florida Groundwater Regulations</td>
<td>Perchlorate</td>
<td>Discharges from RSRM post-flight processes</td>
</tr>
<tr>
<td>TSCA</td>
<td>Perfluorinated chemicals</td>
<td>PFOS, PFAS, PFOA in many applications; materials restricted</td>
</tr>
<tr>
<td>RCRA</td>
<td>Perchloroethylene</td>
<td>SRB post-flight removal of hypalon triggered hazardous waste requirements</td>
</tr>
<tr>
<td>Permissible Exposure Limits: OSHA</td>
<td>Cr(VI)</td>
<td>Operations to prevent corrosion aluminum substrates, ET, Orbiter: potential for increased PPE and monitoring</td>
</tr>
<tr>
<td>Permissible Exposure Limits OSHA</td>
<td>Lead</td>
<td>Used in SRB AL topcoat, increased PPE and monitoring</td>
</tr>
<tr>
<td>European Regulations REACH</td>
<td>BFRs, Heavy Metals, other toxic materials</td>
<td>Impacts to industry resulting in materials obsolescence</td>
</tr>
<tr>
<td>European Regulations RoHS</td>
<td>BFRs, Heavy metals, other toxic materials</td>
<td>Impacts to industry resulting in materials obsolescence</td>
</tr>
<tr>
<td>European Regulations WEEE</td>
<td>Leaded solders and leaded electrical components</td>
<td>Orbiter, SRB, SSME, EMU</td>
</tr>
</tbody>
</table>
Shuttle Environmentally-Driven Obsolescence Risks
By Element

**External Tank**
- HCFC-141b
- Cadmium
- Hexavalent Chromium
- High VOC coatings
- Cleaning and verification solvents
- Methyl ethyl ketone
- BFRs
- PFOA

**Orbiter**
- HCFC-141b
- Trichloroethane
- Cadmium
- Hexavalent Chromium
- Methyl Ethyl Ketone
- High VOC coatings
- Lead-free electronics
- Hazardous Air Pollutant Inks
- Cleaning and verification solvents
- Methyl ethyl ketone
- PFAS
- BFRs
- PFOA

**Space Shuttle Main Engines**
- Hexavalent Chromium
- Cadmium
- Lead-free electronics
- Cleaning/verification solvents
- PFOA

**Reuseable Solid Rocket Motors**
- HCFC 141b
- Trichloroethane
- Cadmium
- Hexavalent Chromium
- High VOC Coatings
- Hypalon
- Lead-free electronics
- BFRs
- PFOA

**Ground Support**
- Cadmium
- Hexavalent Chromium
- PFOA

**Solid Rocket Boosters**
- HCFC-141b blowing agent
- Hexavalent Chromium
- Lube-Lok
- High VOC Coatings
- Hypalon paint
- Lead-free electronics
- BFRs
- PFOA

**Flight Crew Equipment/Space Suit**
- Hexavalent Chromium
- Lead-free electronics
- BFRs
- PFOA
## Status Shuttle Environmentally-Driven Materials Obsolescence Risks 2001-2010

<table>
<thead>
<tr>
<th>Risk Description</th>
<th>2001</th>
<th>2006</th>
<th>2010</th>
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</thead>
<tbody>
<tr>
<td>1,1,1 Trichloroethane (Orbiter use)</td>
<td></td>
<td></td>
<td>ACCEPTED</td>
</tr>
<tr>
<td>1,1,1 Trichloroethane (RSRM use)</td>
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<td>CLOSED</td>
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<tr>
<td>Cadmium Replacement in Plating Applications</td>
<td></td>
<td></td>
<td>ACCEPTED</td>
</tr>
<tr>
<td>Hexavalent Chromium Replacement in Primers</td>
<td></td>
<td></td>
<td>ACCEPTED</td>
</tr>
<tr>
<td>Hexavalent Chromium Replacement in Conversion Coat</td>
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<td></td>
<td>ACCEPTED</td>
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<tr>
<td>Chemical Paint Stripper Alternatives</td>
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<td></td>
<td>ACCEPTED</td>
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<tr>
<td>Alternate Dry-Film Lubricant</td>
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<td>CLOSED</td>
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<tr>
<td>High Volatile Organic Compound Coatings</td>
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<td>ACCEPTED</td>
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<tr>
<td>Hypalon Paint (perchloroethylene)</td>
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<td></td>
<td>CLOSED</td>
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<tr>
<td>Lead-Free Electronics</td>
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<tr>
<td>Hexavalent Chromium in Alkaline Cleaners</td>
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<td></td>
<td>CLOSED</td>
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<tr>
<td>Hazardous Air Pollutant Inks</td>
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<tr>
<td>Methyl Ethyl Ketone</td>
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<td></td>
<td>CLOSED</td>
</tr>
<tr>
<td>Precision Cleaning and Verification Solvents</td>
<td></td>
<td></td>
<td>CLOSED</td>
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<tr>
<td>Perfluoroalkyl Sulfonates</td>
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<td>CLOSED</td>
</tr>
<tr>
<td>Brominated Flame Retardants</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>HCFC 141b Blowing Agent</td>
<td></td>
<td></td>
<td>CLOSED</td>
</tr>
<tr>
<td>PFOA perfluorooctanoic acid</td>
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</tbody>
</table>
Major Mitigation Approaches

CFC 11 (Class I ODS)
• Replaced with HCFC 141b (Class II ODS) as the blowing agent in Thermal Protection System foam on the External Tank

CFC 113 (Class I ODS)
• For most cleaning applications, aqueous cleaners were qualified and implemented
• For ET, CFC-113 was replaced with HCFC-225 in clean room cleaning operations for all LOX and most liquid hydrogen compatible hardware.
• Some applications still required a final CFC-113 flush for cleanliness verification

Trichloroethane (TCA, Class I ODS)
• Replacement depended on application
• Aqueous processes, d-limonene, Vertrel MCA, Isopropyl alcohol, AK225G, and others
• TCA still required for rubber activation on RSRM: Essential Use Exemption /Stockpile

HCFC 141b (Class II ODS)
• More than 200 blowing agents were researched. No viable material was found that met the ET requirements.
• Exemption allowance for production and use on specific SSP applications
Major Mitigation Approaches

Hexavalent chromium

• Cr(VI) was commonly used in primers and coatings for Al surfaces because of its effectiveness in preventing corrosion.

• SSME: Chromated coatings were replaced with TT-P-2756, a non-chromated, VOC-compliant, self-priming topcoat.

• SRB: conversion coating replacement qualified was Alodine® 5700 (Henkel). The primer and topcoat replacements qualified were Hentzen Coatings, Inc. 05510WEP-X/05511CEH-X primer and 4636WUX-3/4600CHA-SG topcoat.

• Orbiter: Largest effort was focused on the corrosion resistant primer Super Koropon®. Akzo Nobel 10PW22-2 non-chromated, low-VOC, replacement primer was implemented on a limited basis.

Cadmium

• The SSP Elements replaced many of the Cd-plated bolts used on the shuttle with bolts coated with various alternative metallic coatings.

• The SSP ET used thousands of Cd-plated parts on several different substrates in hundreds of different applications, the majority of which were high-strength fasteners.. ET conducted down-select testing of tin-zinc and zinc-nickel and recommended the zinc-nickel system as a Cd replacement alternative.
Major Mitigation Approaches

Lead Free Electronics

• Purchasing contracts stipulated that vendors had to notify the SSP of any material changes, but distributors often did not know about changes made in original equipment manufacturers’ processes.

• SSP Elements inspected their existing parts, checked new parts, and monitored part suppliers to ensure adequate lead was included to protect critical circuitry.

• Where necessary, the SSP Elements stockpiled critical lead-containing parts to ensure an adequate supply of reliable materials.

• Orbiter performed x-ray fluorescence spectrometry testing on a subset of the orbiter inventory and concluded that the older orbiter parts were less of a concern than more recently purchased industry parts, so careful monitoring of new parts was implemented.
NASA Space Launch System (SLS) Under Development

Orion Multi-Purpose Crew Vehicle

Interstage

Launch Abort System

Core Stage

RS-25 Engines (Space Shuttle Main Engines)

Solid Rocket Boosters

Payload Fairing

Upper Stage with J-2X Engine

Liquid or Solid Rocket Boosters

70 t
321 ft.

130 t
384 ft.
Future Materials Obsolescence Challenges

• SLS and other NASA Programs will continue to face environmentally-driven materials obsolescence risks
• SLS will face materials obsolescence risks similar to those faced by the Shuttle
• REACH will have bigger effect:
  – chemicals on REACH Substances of Very High Concern (SVHC) list
  – difficult to identify potential applications and resulting risk
  – materials commonly used on space vehicles on REACH authorization list
• Uncertainty on continued availability of materials and changes made by vendors
• ODSs, hexavalent chromium, cadmium, lead free solder, brominated flame retardants, perfluorooctanoic acid
Lessons Learned

• Expect continuous change in environmental risk drivers

• Materials obsolescence can be driven by regulation, vendor changes, technology and market forces

• Regulatory screening, evaluation and risk assessment is critical

• Coordinated, team approach is best practice

• All stages of a project life cycle should involve environmental assurance discipline

• Material obsolescence can be a major cost to programs and projects

• Material stockpiles have limited sustainability and may be costly, but sometimes are the only option

• Important to know where materials are/will be used and criticality

• Formulation changes can occur in numerous ways
  --primary ingredient change
  --processing chemical change
  --process change
  --supplier change