Specifying and testing CUI protective coating systems

Engineer’s Specification Guide for CUI Coatings

Bart Martens | NACE JUBAIL Technical Workshop Corrosion Under Insulation
Presentation outline

Three items from the invitation will be addressed:

KEY SESSIONS AND TOPICS

- CUI Design Parameters and Key Factors.
- Insulation Materials and Selection Criteria.
- Best Practices in Maintenance to enhance Material Life-cycle and minimize corrosion.
- CUI Advance Inspection Technologies.
- Non-Destructive Testing Methodologies and Techniques.
- CUI Mechanisms and Causes.
- Advanced Coating System for CUI protection.
Presentation outline

**Design parameters**
- Coating system for hot exposure: how hot is hot?

**Coating systems**
- Testing and choosing a protective coating system

**Maintenance**
- Substrate condition
Design parameters
Coating system for hot exposure: how hot is hot?

**Maximum temperatures**
- Vary with coating chemistry
- Are not the only selection criteria
### Maximum exposure

**Traditional coating systems: atmospheric/under insulation**

<table>
<thead>
<tr>
<th>Coating System</th>
<th>Maximum Temperature</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy/PU atmospheric systems</td>
<td>&lt;80-120°C</td>
<td>*</td>
</tr>
<tr>
<td>Some epoxy coatings/linings</td>
<td>&lt;150°C</td>
<td>@</td>
</tr>
<tr>
<td>Special alkyd systems</td>
<td>&lt;175°C</td>
<td></td>
</tr>
<tr>
<td>Some (phenolic) epoxy</td>
<td>&lt;200°C</td>
<td>@</td>
</tr>
<tr>
<td>Special phenolic epoxy</td>
<td>&lt;230°C</td>
<td>@</td>
</tr>
<tr>
<td>Silicone acrylic</td>
<td>&lt;350°C</td>
<td>**</td>
</tr>
<tr>
<td>Zinc silicate</td>
<td>&lt;400°C</td>
<td>***</td>
</tr>
<tr>
<td>Silicone aluminium</td>
<td>&lt;540°C</td>
<td>**</td>
</tr>
</tbody>
</table>

**Notes:**

* Sometimes requested/specified as 150°C (without PU topcoat)
** With or without zinc silicate primer
*** Without a topcoat
@ under insulation only for approved systems
### Typical Protective Coating Systems for Carbon Steels Under Thermal Insulation and Fireproofing

<table>
<thead>
<tr>
<th>System Number</th>
<th>Temperature Range (A) (B)</th>
<th>Surface Preparation</th>
<th>Surface Profile, µm (mil) (C)</th>
<th>Prime Coat, µm (mil) (D)</th>
<th>Finish Coat, µm (mil) (D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS-1, CS-2, CS-3</td>
<td>Epoxy, Fusion Bonded Epoxy, Epoxy Phenolic minus 110° to 302°F [minus 45° to 150°C]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CS-4</td>
<td>-45° to 205°C (-50 to 400°F)</td>
<td>NACE No. 2 / SSPC-SP 10</td>
<td>50-75 (2-3)</td>
<td>Epoxy novolac or silicone hybrid, 100-200 (4-8)</td>
<td>Epoxy novolac or silicone hybrid, 100-200 (4-8)</td>
</tr>
<tr>
<td>CS-5</td>
<td>-45° to 595°C (-50 to 1100°F)</td>
<td>NACE No. 1 / SSPC-SP 5^{15}</td>
<td>50-100 (2-4)</td>
<td>TSA, 250-375 (10-15) with minimum of 99% aluminum</td>
<td>Optional: Sealer with either a thinned epoxy-based or silicone coating (depending on maximum service temperature) at approximately 40 (1.5) thickness</td>
</tr>
<tr>
<td>CS-6</td>
<td>-45° to 650°C (-50 to 1200°F)</td>
<td>NACE No. 2 / SSPC-SP 10</td>
<td>40-65 (1.5-2.5)</td>
<td>Inorganic copolymer or coatings with an inert multipolymeric matrix, 100-150 (4-6)</td>
<td>Inorganic copolymer or coatings with an inert multipolymeric matrix, 100-150 (4-6)</td>
</tr>
<tr>
<td>CS-7</td>
<td>Petroleum wax primer; ambient to 140°F [60°C]</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>CS-8</td>
<td>Shop primers and topcoats for inorganic zinc (IOZ) minus 110° to 750°F [minus 45° to 400°C] Novolac, phenolic, inorganic copolymer and inert polymeric matrix</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Cyclic Service
No clear definition

Frequency: number of cycles per
• Day / Week
• Month / Year

Regularity
• Always the same hot and cold periods?
• Duration of hot and cold periods.
• Lowest and peak temperatures.

Gradients
• How quickly does the temperature go up and down?
Different heat cycles

- **Dry** (low corrosion pressure)
- **Evaporation/Steam** (especially under insulation)
- **Ambient: Condensation/Wet**

May be limited to and X days per cycle and <10% of the time for certain products.
Less regular cycles

**Peak**
- $\gg 230^\circ C$ and peaks $>540^\circ C$
- Inorganic co-polymer /multi-polymeric matrix

**Initial ambient phase**
- Long: low DFT system may not be suitable
- early corrosion.
- Extra DFT (barrier) to be considered if possible

**Cycle**
- Less frequent cycle
- Longer hot periods vs cold

**Peak**
- Varying temperatures
- $>200^\circ C$
- Only some (phenolic) epoxy systems

**Cycle**
- Less frequent
- More time at ambient than hot
- Higher DFT system preferred.
- Chemical resistance

Specifying and testing CUI protective coating systems
Corrosion protection (barrier effect)

- Blasting profile of 50µm: Peaks covered?
- Barrier against moisture, impact and abrasion?
- Active galvanic protection.

**Silicone (acrylic)**
- 2 coats of 25µm
- Total DFT = 50µm
- Barely covers peaks
- Suitable under insulation?
- OK for galv and SS?

**Zinc & Silicone (acrylic)**
- 75µm zinc primer
- 2 coats of 25µm
- Total DFT = 125µm
- Galvanic protection (sacrificial, sealed)
- Covers peaks
- Suitable under insulation?
- NOK for galv and SS!

**Phenolic or multipolymeric matrix**
- 2 coats of 125µm = 250µm
- Covers peaks + 200µm
- Extra barrier in 3 coats possible
- OK under insulation.
- OK for galv and SS!
What about cryogenic?

Atmospheric corrosion pressure is low below 0°C
- No liquid water
- Lower temperatures means slower chemical reactions

Ice and condensation
- Ice: potential mechanical stress
- Condensation: semi immersed situation, not pure atmospheric
  may affect the recoat window of some primers

All coatings become brittle when cooled to cryogenic temperatures
- Far below their glass transition temperature, Tg
- Most epoxies/PU systems perform well until -40°C
  Winter exposure in countries like Canada, Russia etc.
- Strength / flexibility will be needed at lower temperatures
- especially in combination with (rapid) cycling

Specifying and testing CUI protective coating systems
Selecting coating systems: Physical Performance

**Wide choice of protective coating systems**
- NACE SP0198-2010

**CUI is often the most severe corrosion**
- entrapment of chlorides and sulfides
- rapid spread of corrosion to other areas

**Coating chemistries**

**Testing standards for CUI coating systems will be discussed**
Design Criteria of CUI Coatings
Physical and resistance properties

- Resistance to thermal shock & cycling
- Resistance to thermal aging
- Chemical resistance
- Intermittent hot & boiling water immersion
- Flexibility and toughness to handle varying thermal gradients
- Matched CTE over temperature range
Classification of CUI Coatings

- Metallic Coatings; TSA, TSZ, Galvanized, Aluminized
- Inorganic ceramic composites
- High Build Aluminium, Titania Siloxane Composites
- Modified epoxies phenolic / novolac, MIO / glass filled
Metallic Coatings - TSA
Thermal Spray Aluminum Ambient to 1200° F [650°C]

• TSA coatings form a mechanical bond to the substrate
• SSPC-SP 10 “Near White Blast” for surface preparation is critical
  • Limited suitability for maintenance.
• Coefficient of Thermal Expansion not matched to the substrate
  • Thermal cyclic conditions will affect TSA: internal stresses
• Good permeability resistance under non-insulated isothermal conditions at lower temperature range up to 392°F [200°C]
• Limited chemical resistance
• TSA can lose on average one mil [25 microns] or more per year based on recent case studies
Chemical Attack of Aluminium

**Reaction of aluminum with halogens**
- Aluminum metal reacts vigorously with all halogens. It reacts with chlorine, Cl₂, bromine, Br₂, and iodine, I₂.
  - 2Al(s) + 3Cl₂(l) → 2AlCl₃(s)
  - 2Al(s) + 3Br₂(l) → Al₂Br₆(s)

**Reaction of aluminum with acids**
- Aluminum metal dissolves readily in dilute sulfuric and hydrochloric acid to form solutions containing aquated aluminum species.
  - 2Al(s) + 3H₂SO₄(aq) → 2Al³⁺(aq) + 2SO₄²⁻(aq) + 3H₂(g)
  - 2Al(s) + 6HCl(aq) → 2Al³⁺(aq) + 6Cl⁻(aq) + 3H₂(g)

**Reaction of aluminum with bases**
- Aluminum dissolves in sodium hydroxide with the evolution of hydrogen gas, H₂, and the formation of aluminates of the type [Al(OH)₄]⁻.
  - 2Al(s) + 2NaOH(aq) + 6H₂O → 2Na⁺(aq) + 2[Al(OH)₄]⁻ + 3H₂(g)
Inorganic Ceramic Inert High Build Coatings
302°-1200°F [150°-650°C]

- Chemical bonding to the substrate (covalent)
- Surface tolerant with minimum substrate preparation
- CTE near match to substrate
  - Excellent thermal cyclic resistance to include cryogenic service
- High build capability up to 18 mils [450 um]
- Open recoat window / single component
- Good chemical resistance
Metallic High Build Universal Coatings
Aluminum & TiO₂ Ambient to 840°F [450°C]

- Metallic, inorganic co-polymer coatings form a mechanical / interfacial polar bond to the substrate
- SSPC-SP 10 “Near White Blast” for surface preparation is critical
- Severe thermal cyclic conditions will affect metallic coatings over time due to internal stresses
- Good permeability resistance under isothermal conditions
- Poor chemical resistance
Epoxy Phenolic / Novolac
Ambient to 400°F [204°C]

- Interfacial polar to polar hydrogen bonding to the substrate
- Organic composition limits temperature window
  - Reinforced and specialized formulations peak > generically similar types
    - Generic pure epoxy 120-150°C
    - Some glass or mio versions withstand 200°C
- Good permeability resistance
- Cyclic resistant
- Short overcoat window
- Good chemical resistance
- Application up to 150°C substrate possible for some products
Typical Test Methods for Elevated Temperature Coatings

• **ASTM B-117:**
  - Salt Fog Chamber 3500–4500 hours

• **ASTM 2485:**
  - This test ensures adhesion based on CTE after severe thermal shock

• **ASTM 2402:**
  - Mass loss is critical in determining the porosity and longevity of a coating

• **EIS Testing:**
  - Electrical Impedance Spectroscopy, permeability before and after thermal exposure
ASTM D 2485

**Typical Procedure**

- Coated finished panels are placed in a muffle furnace with the following schedule:

  - 205°C (400°F) - 8 hours – quench
  - 260°C (500°F) - 16 hours – quench
  - 315°C (600°F) - 8 hours – quench
  - 370°C (700°F) - 16 hours – quench
  - 425°C (800°F) - 8 hours – quench
  - 538°C (1000°F) - 16 hours – quench
ASTM E2402 Mass Loss

![Graph showing Mass Loss vs Temperature]
### ASTM 2402 Mass Loss Comparison

<table>
<thead>
<tr>
<th>Product</th>
<th>Weight Loss (in percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>400°F 204°C</td>
</tr>
<tr>
<td>Inorganic Ceramic</td>
<td>1.0</td>
</tr>
<tr>
<td>High Build Cold Spray Aluminum</td>
<td>1.5</td>
</tr>
<tr>
<td>Inorganic Co-Polymer / Aluminum Titania Siloxane</td>
<td>1.8</td>
</tr>
<tr>
<td>Glass Filled or MIO Filled Phenolic Novolac Epoxy</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Permeability is minimized as impedance is increased.
Values of $> 10^6 \text{ohms} \cdot \text{cm}^2$ indicate good barrier effect / corrosion protection.
Specific CUI Test Methods

- Shell Test; Cyclic Wet / Dry Immersion Testing 16 weeks
- Steam Bypass Test 90 days
- Modified Houston Pipe Test 21-30 days
- ASTM G189
- PPG HTC CUI Chamber Test (1008 hours, 252 cycles)

Other tests only focus on dry exposure and/or thermal shock.
Shell CUI Cyclic Test 2001 - 2002

**Test protocol:**
Week days (5 days)
- Dry heat exposure at 400°F [208°C] for 16 hours, then quenched in cold water
- Immersion and steam-out exposure at 210°F [99°C] for 8 hours

Weekend (2 days)
- Dry heat exposure in an oven at 400°F [204°C]

**TOTAL TEST DURATION**

- Total Heat Exposure: 2240 hours
- Number of Thermal Quenches: 80
- Total Time of Immersion in 210°F [99°C]: 640 hours

16 weeks
CUI Steam Bypass Test 2011

T₁ - 160°C, T₂ - 155°C, T₃ - 140°C

- Cyclic Profile
  90% Continuous
  10% Downtime

- Solution of 100ppm NaCl + 100ppm Sulfur

- C1 through C4 – Various coatings

- Spray Application – Surface prep SSPC-6 Blast

This is a typical on-site test, not accelerated or controlled
Modified Houston Pipe Test 2010

Cycle description:
- Add 1 liter water (1% NaCl)
- Heat for 8 hours to produce a thermal gradient
- Add 1 more liter of salt water
- Allow to cool to ambient for 16 hours

After 30 cycles the pipe is removed from test and the coating evaluated.

Vertical steam-out/dry simulation
70+% of CUI occurs in the horizontal plane
Not accelerated cyclic immersion test
ASTM G189 - 2007

**Simulation of CUI**
- Iso-thermal or Cyclic
- Wet / Dry

**Can be used to test**
- CUI effect on substrate material
- Insulation material
- Coatings
CUI Chamber Test 2008

**Uses ASTM G189 as a model**
- For simplicity the insulation is omitted
- Temperature control: ambient to 250°C
- Consistent and repeatable results.
- The chamber environment can be totally controlled

**Approvals: Shell Oil 2008, Aramco 2010**

**Method B:**
- 5% NaCl solution
- Set wet/dry cycle time [4 hours]
- 42 day duration [252 cycles] 1008 hours
- Internal temp 350°F [179°C]
- Steam-out immersion temp 212°F [100°C]
Chamber Cross Section

316 SS Chamber
Vapor State
Hot Oil From Heat Exchanger
Drip Plane
Tempered Viewing Glass

To Pump
[Media & Cycling Control]

Seam Coating
Media

Hot Plate Temp Range: 20°-250° C

D.Betzig 2010

Specifying and testing CUI protective coating systems
CUI Test Examples

Before Test

After 6 Weeks Front View

After 6 Weeks Bottom View
Maintenance

Substrate condition

Review

• Type of substrate
  • Coated: coating condition?
  • Carbon steel or stainless steel
• Corrosion
  • Review causes
  • Wall thickness review: still in spec?
  • Remove rust (adhesion issue) to agreed standard Sa2 or Sa2½, St2, St3
• Roughness
  • Pitting corrosion: review material thickness
  • Review coating suitability and required thickness
• Contaminants
  • Sources of osmotic blistering (during ambient phase)
**Maintenance**

**Substrate condition**

**Surface cleanliness**

- Is achievable standard acceptable for the type of coating?
  - Zinc silicate primers and phenolic epoxy require Sa2½
  - Some products can be applied on solvent or detergent cleaned stainless

**In service application: substrate temperature**

- In maintenance substrate temperature may be elevated or increase shortly after application.
- Some epoxy products are suitable for 90-150°C substrate at application.
- Inorganic ceramic inert (multi-polymeric) coatings are available for application on substrates up to 316°C/600F.
- Application technique may be slightly different: building up thickness in multiple passes to allow solvents to evaporate or coating to “set”.
- Safety of solvent based material in a “hot” environment: flash point vs. self ignition temperature.
Product selection: ease of use
Flexibility in specifying and application

- **Single component**
  - Open recoat window
  - No mix-volume measuring for smaller applications

- **Surface & application tolerant**
  - Spray, brush or roll
  - Adherent to welds
  - Easily repaired at ambient or on hot surfaces
  - Field repairs and tie-ins with limited surface preparation
  - Field repairs and tie-ins with same coating system

- **Cost effective**
  - Requiring minimal surface preparation

- **High DFT**
  - Extended CUI protection (for extended ambient exposure)
  - Crack resistance

- **“Constructability”**
  - Robust enough to transport / lay down / erect with minimal repair
  - Minimal damage from insulation and cladding installation
Conclusions

Coating vs CUI Requirements

**Coating must withstand:**
- the process temperatures (design and operational range e.g. 200° to 500°C)
- the actual exposure scenario (cyclic, iso-thermal, wet/dry/immersion exposure, thermal shock, steam-out)
- the most corrosive temperature range of 150° to 180°C
- chlorides, halides and sulfides and intermittent pH in the range of 5 to 10
- accelerated CUI Test

**And must:**
- be compatible with the specified substrate: carbon, duplex and austenitic stainless steels
- be suitable for insulated and non-insulated service
- have chemical resistance to have good (chemical) bonding to substrate
- have CTE designed to minimize surface tension
- Meet application requirements:
  - New construction
  - Maintenance

Specifying and testing CUI protective coating systems
Conclusions

State of the Art CUI coating technology - 150° to 650°C

Inorganic ceramic inert coatings offer the best overall performance for high temperature cyclic and isothermal conditions

- CTE is matched closely to the substrate
- Limited mass loss: <8% at 400°C
- Chemical bonding to the substrate and good overall chemical resistance (intermittent pH 5-10)

These coatings are single component and user friendly, with open recoat windows allowing ease of maintenance and extended life
Questions

Specifying and testing CUI protective coating systems