A Solvent Cleaning Process for the Outer Surfaces of Plastic ICF Capsules

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Isolated contaminants on an ICF capsule can lead to undesirable instabilities during implosion.

Haan specification for particulates on capsule:

- 1.5 – 2.5 um: 50
- 2.5 – 3.0 um: 10
- >3.0 um: 0

This particle is >400 pg.
Cleaning process must be...
- Capable of removing particles of various sizes, shapes, bonding mechanisms, etc.
- Global and robust
- Mechanically friendly to the fill-tube bond
- Safe for the operator and environment
Capsule contaminants are typically flat and organic

A typical capsule will have <10 offending particles
Before and after maps of capsule surface are obtained by automated confocal microscopy ("4π")
Detachment strategy relies on hydrodynamic force overcoming van der Waal’s adhesion force

- vdW forces depend on material, particle size, contact distance

\[ F_{\text{adh}} = \frac{A R}{8\pi h_o^2} \]

- Hydrodynamic force depends on fluid velocity/properties, particle size

\[ F_H = 32 \mu R v_x(R) \]

<table>
<thead>
<tr>
<th>Particle diameter (µm)</th>
<th>Force (N)</th>
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<tbody>
<tr>
<td></td>
<td>$10^{-11}$</td>
</tr>
<tr>
<td></td>
<td>$10^{-10}$</td>
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<tr>
<td></td>
<td>$10^{-9}$</td>
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<td>$10^{-8}$</td>
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<td>$10^{-7}$</td>
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<td>$10^{-6}$</td>
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We have developed a two-step process using both chemical and physical forces to remove particles.

**Initial:** Tightly bound organic particle on dry CH surface

**Step 1:** Chemically dislodge via swelling and/or wetting

**Step 2:** Physically entrain and remove by applying hydrodynamic force
Ideal solvent decreases adhesion energy through a combination of swelling and/or wetting

Water

Organic solvent

Poor wetting due to high surface energy (70 dyne/cm)

Most organics have low surface energy (~20 dyne/cm)

We have selected ethanol due to its rapid boiling, low surface energy, and environmental/operator friendliness
Higher hydrodynamic forces can be achieved by angling the stream with respect to the surface.
Process variables can be systematically changed on flat proxy samples to understand entrainment step.

**Stream motion on a sphere**

Key variables: flowrate ($Q$), raster speed ($v$), step size ($\delta$)

**Stream motion on a plane**

Annealed CH is doped with 1-5 um spherical particles

$Q$ represents removal force, $v$ represents stream dwell time, and $\delta$ represents stream surface coverage.
Efficient particle removal can be achieved by high flowrates and low raster rates

Cleaning efficiency in $v$-$Q$ process space

Size and color of marker represents fraction of isolated 1 um spherical particles removed during cleaning

Insufficient dwell time cannot be compensated for by increased force

A minimum force is required
Entire capsule surface needs to be covered by a slow-moving stream for effective cleaning

Cleaning efficiency in $v$-$\delta$ process space

Size and color of marker represents fraction of isolated 1 um spherical particles removed during cleaning

- High surface coverage but insufficient dwell time
- Long dwell time but insufficient surface coverage

$Q = 3$ cc/min
The largest forces are exerted at the leading edge of the fluid stream.

We cannot know the removal force for an arbitrary particle, but effective stream area is likely limited to the contact zone.
Experiment + model suggest requirements for efficient particle removal in time and space

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Quantitative conclusion</th>
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<tbody>
<tr>
<td>Adhesion force must be reduced chemically</td>
<td>Methyl formate or other organic (~20-25 dyne/cm)</td>
</tr>
<tr>
<td>Hydrodynamic force exceeds adhesion force</td>
<td>~3x10^{-9} N for 1 um spheres</td>
</tr>
<tr>
<td>Sufficient dwell time of stream in a given spot</td>
<td>~0.2 sec for 1 um spheres</td>
</tr>
<tr>
<td>Sufficient coverage of stream over surface</td>
<td>~100% coverage for 1 um spheres</td>
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</table>

These results provide a roadmap for cleaning recipes: high stream velocity, long dwell times, and full coverage of the capsule
We have integrated these requirements into an automated system that we are currently qualifying.
Pilot cleaning of five capsules showed good cleaning efficiency of >30 um³ particles.
Automated, high-throughput capsule cleaning with a mechanically controlled system

Combination of chemical action (solvent choice) and physical entrainment (stream kinematics) can clean simulated surfaces with high efficiency

Mechanical design can automate cleaning while minimizing risk to capsule and ensuring operator and environmental safety

Need to complete qualification of cleaning station and gather statistics on production CFTA cleaning efficiency
Future development work will focus on wand-capsule interactions

Wand is not entirely benign

Observed failures: scuffing, debris, residue, imprinting

- Potential areas of improvement for mitigating the effect of the wand
  - Wand geometry
  - Wand material
  - Wand surface finish
  - Maintenance cleaning of wand
  - Vacuum level
  - Drying assistance
  - ...