Effect of Tritium-Induced Damage to Plastic Targets from High-Density D-T Permeation

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The DT-filled glow-discharge-polymer (GDP) cryogenic targets do not exhibit an outer-diameter (OD) decrease when cold

- Diameters of cryogenic targets are measured with a calibrated imaging diagnostic
- The estimated $\sim 13-\mu\text{m}$ contraction of DT-filled GDP capsules when cooled to cryogenic temperatures is not observed
- Unfilled and D$_2$-filled GDP capsules do contract by $\sim 10 \ \mu\text{m}$ when cooled
- DT-filled polystyrene (PS) capsules also contract by an amount predicted by their thermal-expansion coefficient

Radiation damage to the highly cross-linked GDP may be the explanation—polystyrene is one of the most radiation-resistant polymers.
The DT-filled GDP cryogenic targets do not exhibit an OD decrease when cold

- Cryogenic target OD’s were being measured in the cryogenic target characterization stations with OD’s up to 13 $\mu$m greater than expected from thermal contraction after cooling

- The expected diameters were calculated from the General Atomics’ (GA) NIST*-traceable room-temperature measured OD value and the coefficient of thermal expansion of GDP—this contraction was not observed

- As a secondary effect, mismeasurement of the OD can influence the reported fuel-layer thickness.

- To examine this effect, several experiments were performed including
  - optical system calibration check
  - comparison of OD measured in cryo system with NIST*-traceable value ($864.1 \pm 0.5-\mu$m OD silicon ball measured at GA)
  - parameter study of what system variables can affect the OD measurement
  - opaque versus transparent sphere comparison

*National Institute of Standards and Technology
The magnification and distortion of the optical system is measured using an array of dots with a known spacing.

The total length of 30, 10-μm-diam dots was measured in both the x and y directions to give:

\[ x \text{ pitch} = 19.99 \mu m \]
\[ y \text{ pitch} = 19.97 \mu m \]

Manufacturer’s quoted pitch:
\[ x \text{ pitch} = y \text{ pitch} = 20.0 \pm 0.1 \mu m \]

The (Rayleigh criterion) diffraction-limited resolution of the f/5 imaging lens = 3.8 μm; sampling the perimeter every degree gives an OD resolution = 0.5 μm.
Several parameters were varied to determine their effect on the measured outside diameter

- Illumination intensity—effect if background is saturated
- Illumination geometry (numerical aperture)—no effect
- Focus shift—effect only if image is noticeably blurry
- Position of the capsule along the optical axis of the imaging system—no effect
- Position of the capsule laterally in the field of view—no effect
- Characterization station—no effect
- Moving-cryostat transfer cart—no effect
- Opaque versus transparent sphere—no effect

All OD measurements labeled “no effect” were 3-μm greater than the NIST-traceable OD—needed to modify edge-detection algorithm.
The outside diameter is underestimated by 7 µm only when the image is severely out of focus.

In-focus image
OD = 867.2 µm

Noticeably out of focus
OD = 867.2 µm

Grossly out of focus
OD = 860.2 µm

The OD is measured at the center of the gradient from light to dark in the image. This produces an accurate measurement despite being noticeably out of focus.
A saturated background causes “blooming” that erodes the perimeter and reduces the measured OD by 5 \( \mu m \).

The measurement is consistently 3 \( \mu m \) greater than the NIST-traceable Si-ball diameter of 864.1\( \pm \)0.5 \( \mu m \) OD; this is systematic error that can be corrected in the measurement software.
A saturated background also causes “blooming” to erode the perimeter of the transparent GDP capsule.

Correct illumination, LED current = 900 mA
OD = 869.2 μm

Low-light illumination, LED current = 100 mA
OD = 869.4 μm

Saturated background, LED current = 2100 mA
OD = 862.2 μm

The saturated image background underestimates the OD by 7 μm.
An offset peak in the illumination intensity can also yield a false out-of-round measurement.
The data obtained in one cryo campaign shows typical behavior for DT-filled GDP capsules.

<table>
<thead>
<tr>
<th>Target</th>
<th>Outer diam ((\mu m))</th>
<th>Warm</th>
<th>Measured cold</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRYO-1079-037</td>
<td>873.8</td>
<td></td>
<td>875.7 (+1.9)</td>
</tr>
<tr>
<td>CRYO-1081-027</td>
<td>871.2</td>
<td></td>
<td>874.8 (+3.6)</td>
</tr>
<tr>
<td>CRYO-1081-029</td>
<td>870.2</td>
<td></td>
<td>874.1 (+3.9)</td>
</tr>
<tr>
<td>CRYO-1080-036</td>
<td>873.0</td>
<td></td>
<td>874.2 (+1.2)</td>
</tr>
</tbody>
</table>

Note: two 860-\(\mu m\)-OD, unfilled GDP capsules were cooled from room temperature to 19 K; they both contracted by 9.7\(\pm0.1\) \(\mu m\) (1.1%).
All OD’s, when measured warm or cold, do not differ within the single-measurement uncertainty of the OD.

The warm OD (GA) and cold OD (LLE) differ, on average, by $0.06 \pm 1.2 \, \mu m$ or $0.01 \pm 0.13\%$.

(3-\mu m systematic error not corrected in these data)

These data are for 129 DT-filled GDP capsules from 8/26/2014 to 12/8/2015 ordered in increasing $\Delta$OD.
Various correlations of OD change with other parameters were examined; none were significant.

The GDP capsules containing thicker layers were exposed to DT longer and at higher concentrations during permeation, yet there is no strong correlation of OD change with layer thickness. This would imply damage and swelling occurs early in the process and concludes quickly.
The cryogenic-target database was mined to see if links existed between these parameters and $\Delta$OD measurements:

- Date of capsule fill—no correlation
- DT layer thickness—no correlation
- Moving-cryostat transfer cart—no correlation
- Characterization station—no correlation

![Graphs showing correlation between various parameters and $\Delta$OD](image-url)
DT-filled polystyrene capsules exhibited contraction

<table>
<thead>
<tr>
<th>Target</th>
<th>Outer diam (μm)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Warm</td>
<td>Cold</td>
<td></td>
</tr>
<tr>
<td>CRYO-9079-18</td>
<td>875.0</td>
<td>868.8</td>
<td>(−6.2)</td>
</tr>
<tr>
<td>CRYO-9083-12</td>
<td>869.0</td>
<td>862.4</td>
<td>(−6.6)</td>
</tr>
<tr>
<td>CRYO-9089-37</td>
<td>868.0</td>
<td>860.4</td>
<td>(−7.6)</td>
</tr>
<tr>
<td>CRYO-9088-38</td>
<td>867.0</td>
<td>858.6</td>
<td>(−8.4)</td>
</tr>
<tr>
<td>CRYO-9089-34</td>
<td>869.0</td>
<td>860.3</td>
<td>(−8.4)</td>
</tr>
</tbody>
</table>

The polystyrene capsules contracted an average of 7.4±0.9 μm (0.8%).
One D$_2$-filled GDP capsule also exhibited contraction

<table>
<thead>
<tr>
<th>Target</th>
<th>Outer diam ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Warm</td>
</tr>
<tr>
<td>CRYO-2123-19 04</td>
<td>871.6</td>
</tr>
</tbody>
</table>

The D$_2$-filled GDP capsule contracted by 9.9 $\mu$m (1.1%).

Recall:

Two 860-$\mu$m-OD, unfilled GDP capsules were cooled from room temperature to 19 K; they both contracted by 9.7±0.1 $\mu$m (1.1%).
Total tritiated hydrocarbons in the 1000-ppm range suggest radiation-induced damage to the GDP.

Gas returned from the permeation cell was sampled and analyzed using magnetic-sector mass spectrometry at LLNL.
Summary/Conclusions

The DT-filled glow-discharge-polymer (GDP) cryogenic targets do not exhibit an outer-diameter (OD) decrease when cold.

• Diameters of cryogenic targets are measured with a calibrated imaging diagnostic.

• The estimated ~13-\(\mu\)m contraction of DT-filled GDP capsules when cooled to cryogenic temperatures is not observed.

• Unfilled and D\(_2\)-filled GDP capsules do contract by ~10 \(\mu\)m when cooled.

• DT-filled polystyrene (PS) capsules also contract by an amount predicted by their thermal-expansion coefficient.

Radiation damage to the highly cross-linked GDP may be the explanation—polystyrene is one of the most radiation-resistant polymers.
Backup
The outside diameter of a silicon ball and two mass-equivalent polymer capsules were measured while varying the illumination intensity, illumination geometry, focus shift, position of the capsule along the optical axis of the imaging system, position of the capsule laterally in the field of view, characterization station, and moving-cryostat transfer cart. The greatest effect on OD measurement was illumination intensity, i.e., saturation of the image around the perimeter of the capsule. In addition, if the “center of gravity” of the illumination does not coincide with the optical axis and capsule center, intensity variations around the perimeter can locally affect where the analysis software determines the capsule’s edge. Unsaturated images reproduced the OD measurement even under low illumination. Secondly, focus does have an effect on the OD, but errors are only produced if the image is noticeably out of focus. Overall, the OD was greater than that measured at GA by \( \sim 2 \, \mu m \), which is within the theoretical single-measurement, diffraction-limited resolution of the \( f/5 \) optical system of 3 to 4 \( \mu m \). A USAF 1951 high-resolution target with down to a 0.7-\( \mu m \) linewidth will be purchased in the near future to measure the resolution directly.

The OD of the two mass-equivalent polymer capsules was measured both at room temperature and at 19 K. They both contracted by nearly 10 \( \mu m \), which is 1.1% of their warm OD. These two capsules had never been filled with D-T. A comparison of 129 DT-filled capsules revealed that they contracted by an average of 0.06±1.2 \( \mu m \) or 0.01±0.13%. Again, the uncertainty is within the resolution of the optical system. A lack of the \( \sim 10-\mu m \) anticipated contraction and the overmeasurement of the OD by \( \sim 2 \, \mu m \) can explain the up to 13-\( \mu m \) larger-than-expected OD’s reported by the measurement software.
Fuel layers can be evaluated using visible or near-infrared shadowography

- 2048 × 2048-pixel CCD camera
- Translation and tilt stage
- Near-infrared light-emitting diode (LED) (useful for imaging through foam)
- Zoom objective: 1- to 16-mm field of view (16× zoom)
- ~3-μm resolution at high magnification
- Illumination optics
- Visible LED (720 nm)
The fuel layer is diagnosed by measuring the “bright ring” caused by light reflecting off the inner ice surface.

- Rays that totally internally reflect off of the inner surface of the ice layer form a bright ring in the shadowgraph.
- The internally reflected rays form a caustic that is best focused slightly off the target midplane toward the camera (~40 μm).
- Rays at best focus have been identified as those reflecting off the target’s midplane.
The diametric trace shows the characteristic features of the rings formed by each characterization method.
Unwrapping the images shows similar bright rings including regions with ice-surface defects.
LLE’s OD-measurement algorithm measures the OD by 3 μm greater than the NIST-traceable, GA-measured, room-temperature OD.

DT-filled GDP capsules don’t contract as expected by ~10 μm.

The combination of these two effects explains the ~13-μm discrepancy between the expected and measured OD values.