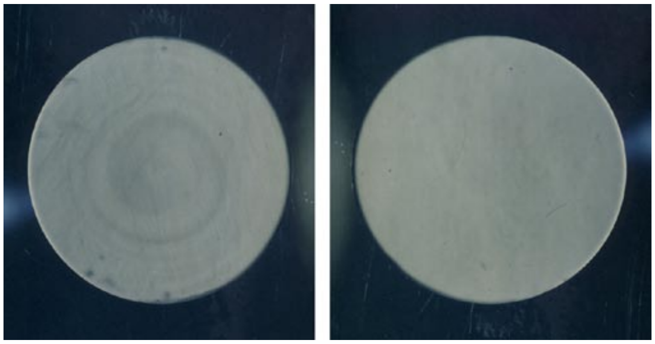
Effect of Molding and Machining on Polychlorotrifluoroethylene

Jess Waller, White Sands Test Facility,
Johnson Space Center

Extrusion of a semitrapped polytetrafluoroethylene (PTFE) pilot seal located in the Orbiter primary reaction control system (PRCS) thruster fuel valve was implicated in 68 fuel failures from late 1994 through 2002. The overall failure rate has remained roughly constant since 1994, with the number of failures typically peaking in years when entire ship sets were returned to WSTF Depot for routine water flushing. However, a rash of six extrusion-related in-flight anomalies thoughout a six-mission span from December 2001 to October 2002 led to heightened activity at various NASA centers, resulting in the formation of a multidisciplinary team to address and solve this problem. Given the unacceptable consequences of multiple thruster failure on the same attitude control axis (mission termination or loss of vehicle control), efforts focused initially on determining the causes responsible for the failures. Once we identified probable causes, we formulated appropriate engineering controls and, to reduce or eliminate further occurrence, began their implementation.

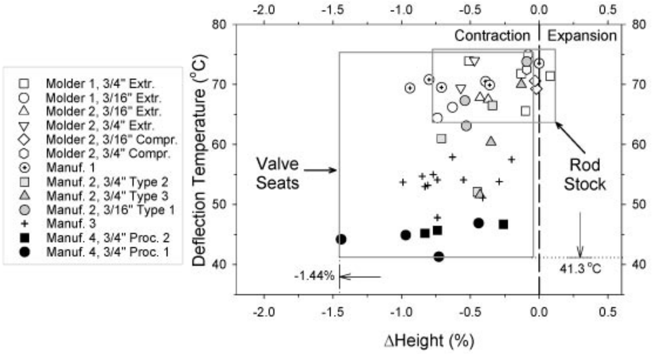
To determine the causes of extrusion, we used a threefold approach consisting of valve-level service history correlations, theoretical calculations and laboratory analyses. For example, a review of service histories showed that extrusion was independent of years in service, mission burns, on time, firing location, and frequency of adjacent oxidizer valve replacements. In addition, while a review of desiccant tube change-out data was largely inconclusive, a review of gaseous helium (GHe) leakage data strongly indicated that extrusion is linked to excessive GHe and oxidizer leakage. We recounted several anecdotal cases wherein thruster fuel valves failed soon after ground oxidizer leakage problems were first noted. Similarly, many premature fuel valve failures were later determined to involve thrusters exhibiting moderate to high GHe leakage.



Observed (symbols) vs. predicted extrusion (dashed lines) for circumferentially welded (left) and intermittently welded (right) extrusion cases.

Estimation of the maximum allowable extrusion due the stress relief of the as-fabricated interference fit revealed that observed levels of extrusion often exceeded the theoretically predicted maximum, suggesting that factors other than thermally-induced extrusion or stress relief were contributing to extrusion (Figure 1). Intermittently welded pilot seat assemblies frequently reached higher levels of extrusion than their circumferentially welded counterparts despite having fewer years in service. Type I extrusion cases, exhibiting both pilot seal id and od extrusion, were determined to be a more advanced form of Type II extrusion (only exhibiting pilot seal od extrusion). Extrusion-related in-flight thruster anomalies were also determined to be of the more severe Type I extrusion category.

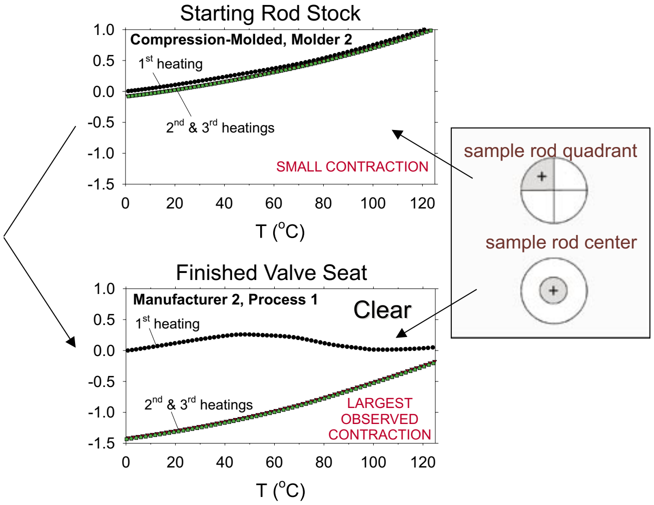
Laboratory analyses were also informative. For example, thermomechanical analysis (TMA) of new pilot seals showed that thermal cycling alone could produce finite amounts of extrusion. However, the levels of extrusion produced by TMA cycling were low, perhaps because of the lack of load-induced lateral cold flow. Additionally, we did not detect a strong link between the extrusion and thermal cycling due vacuum bakeouts, epoxy curing, attitude heating, or the R01 ground fire. Tear-apart failure analyses of failed flight hardware



A representative fuel valve pilot seat assembly cut apart, showing substantial propellant residue inside the pilot seal cavity.

revealed appreciable quantities of fuel-oxidizer reaction product, both on external fuel valve pilot seal surfaces and inside the pilot seal cavity (Figure 2). We confirmed the presence of nitrate anion inside a pilot seal cavity for the first time by ion chromatography and Fourier Transform Infrared Spectroscopy. Component-level exposure tests conducted at WSTF showed that FORP generated in the absence of thruster firing had a similar composition to FORP found in association with Shuttle fleet fuel valves. Specific gravity data on pilot seals from the fleet service showed that extruded seals had significantly lower densities (2.10 g/cc) than seals from oxidizer valves (2.16 g/cc) or flight grade seal preforms machined from bar stock (2.17 g/cc). Differential scanning calorimetry data showed that the FORP observed on exterior surfaces was closely associated with bulk PTFE (Figure 3) and was accumulating near the sealing interface, suggesting a solid-state fuel-oxidizer reaction could be occurring inside PTFE.

We concluded that some thermally induced extrusion is an unavoidable natural consequence of using unannealed, oversized, semitrapped plastic seals in a thruster application. However, oxidizer-induced extrusion is mostly avoidable and mitigation is possible. Parts of mitigation strategies included: implementation of a more effective trickle purge, more stringent GHe leakage requirements, and sensitive diagnostic tests to assess valve reliability. We also mentioned additional improvements stemming from use of better pilot seal materials and the addition of an annealing step during manufacturing.



DSC thermograms (first heating) showing associations between the FORP and a fuel valve (S/N 582) pilot seal (left) and the corresponding lack of FORP observed in an oxidizer valve pilot seal (Exo Up) (right).