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Lessons Learned During Redesign of Shuttle Reaction Control Thruster Pilot Seat Assembly

Jess Waller,* Michael Reynolds,† and Regor Saulsberry‡
NASA Johnson Space Center, White Sands Test Facility, Las Cruces, New Mexico 88004
and
John Albright§
NASA Johnson Space Center, Houston, Texas 77058

Current generation Space Shuttle Orbiter primary reaction control subsystem thrusters have been plagued by problems associated with oxidizer leakage, internal corrosion, and fuel valve pilot seal extrusion. In an effort to fix these problems, and thus improve thruster reliability and reduce life-cycle costs, the pilot-operated valve on the thruster was redesigned. Efforts to improve self-flushing characteristics and minimize oxidizer-induced corrosion within the pilot-operated valve were largely successful; however, a variety of problems stemming from the redesign of the pilot seat assembly within the valve were encountered. The lessons learned from the design, materials selection, and fabrication of the pilot seat assembly are addressed. For example, maximizing the likeness of prototype to final parts and exercising rigorous process control during seal fabrication were found to facilitate the transition from concept to finished hardware. Selection of a suitable polytetrafluoroethylene resin was found to be a predetermining factor in fabrication of viable pilot seals with acceptable mechanical properties. Last, use of a correctly sized and shaped pilot seal preform was found to be essential in preventing excessive and unbalanced stress within the seal during fabrication and in minimizing seal extrusion or recession after fabrication.

Nomenclature

A_{exit} = pilot seal exit (unconfined) area
E_c = compressive modulus, elastic strain limit
T_g = glass transition temperature
V_{cavity} = entrapped pilot seal volume
α = linear coefficient of thermal expansion
ΔL = dimensional change
ΔP = pressure drop across pilot stage
ΔT = temperature change
ε_c^Y = compressive yield strain
σ_c^Y = compressive yield strength

Introduction

THE flow of hypergolic liquid propellants nitrogen tetroxide (oxidizer) and monomethylhydrazine (fuel) to the Space Shuttle Orbiter primary reaction control system (PRCS) thrusters is controlled by a pilot-operated valve (POV). This valve was originally designed and built by Kaiser Marquardt (Van Nuys, California). Operation of the POV involves energizing a solenoid to lift the pilot poppet off the pilot seat [0.5-mm (0.020-in.) stroke], thus venting the pilot cavity and creating a ΔP between the upper and lower cavities of the valve. This ΔP, combined with residual magnetic force in the solenoid, lifts the main poppet off the main seat [1.3-mm (0.050-in.) stroke] to establish full propellant flow through the valve. A cross-sectional view of the POV is shown in Fig. 1. POV performance parameters are given in Table 1.

Between 1981 and 2002, 220 oxidizer and 110 fuel POVs with documented mission firing history failed in-flight or during ground turnaround and had to be replaced. This represents a significant burden to the shuttle program. POV failure modes typically include leakage and failure to open on command. One of the factors implicated in POV failure is corrosion within the oxidizer valves,[1] characterized by significant deposits of brownish-red iron nitrate residue (gelatinous or crystalline, depending on the level of hydration). Nitrate salts not only can cause the valves to stick shut (stiction), but such precipitates, if hard enough, can damage the polytetrafluoroethylene (PTFE) sealing surface. Oxidizer also causes softening of PTFE, leading to additional deformation of the pilot seal under static poppet load or during dynamic valve actuation. In more severe cases, this results in metal-to-metal contact between the poppet and seat adjacent to the pilot seal and subsequent leakage. Another more recent factor implicated in POV failures is extrusion of the fuel valve pilot seal.[2] Pilot seal extrusion is characterized by a excessive [$>127\mu$m (>0.005 in.)] protrusion of the seal above the surrounding metal, thus, restricting propellant flow to the point where insufficient a ΔP is generated to lift the pilot seat assembly off the main stage, thus, preventing full propellant flow from being established to the thruster chamber.

Mitigating oxidizer leakage, corrosion, and seal extrusion problems, thereby improving PRCS thruster reliability, longevity, and life-cycle cost, led to an effort to develop a redesigned POV (RPOV).[3] This effort, involving design, materials selection, fabrication, and valve-level qualification testing of flight configuration RPOV hardware, resulted in numerous lessons learned. These lessons are the subject of this paper.

Materials, Design, and Fabrication

Materials

Two PTFE grades were used in RPOV prototype and flight configuration part fabrication. The first material, Ausimont Algoflon® (Solvay Solexis, Inc., Thorofare, New Jersey) E-2 (A-E2) PTFE (presintered, free-flowing extrusion molding grade) obtained from Interplast (Burlington, New Jersey) per aerospace material specification (AMS) 3658,[4] was used during prototyping (proof-of-concept RPOV design iteration) and during initial efforts to fabricate flight

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*Materials Scientist, Materials Technology Group. Member AIAA.
†Mechanical Engineer, Propellants and Hazardous Fluids Group. Member AIAA.
‡Project Manager, Laboratories Department. Member AIAA.
§Propulsion and Fluid Systems Engineer, Energy Systems Division. Member AIAA.

configuration parts (initial RPOV design iteration). The second material, DuPont Teflon® (E. I. DuPont de Nemours and Company, Wilmington, Delaware) 7A (T-7A) PTFE (as-sintered, non-free-flowing compression molding grade) obtained from EGC Corporation (Houston, Texas) per AMS 3660,[5] was ultimately chosen for all subsequent efforts to fabricate flight configuration parts (final RPOV design iteration). A property comparison of the current POV seal material [T-7A procured under Marquardt Company material specification (MMS) 2517 (Ref. 6)] with the two RPOV seal materials is given in Table 2.

Observed values for the tensile strength and percent elongation of the A-E2 resin were nearly the same as the minimum requirement values specified for T-7A (Table 2). The similarity of these and other properties, coupled with similar material descriptions, more rigorous radiographic inspection requirements for A-E2, and material availability, ultimately led to the choice of A-E2 for the prototyping and initial RPOV design iterations.

Design

The RPOV design objective was to minimize contamination sensitivity of the valve within the geometric and operational constraints of the existing POV. All changes were intended to be transparent to the thruster, propellant feed system, and valve driver circuitry. To address previous failure analysis results and minimize potential impact on interfacing hardware, effort was focused exclusively on the pilot stage of the POV (Fig. 2). In accordance with this objective, emphasis was placed as follows:

1) Reduce oxidizer leakage and associated nitric acid formation, especially in humid air environments.

2) Improve the corrosion resistance of pilot-stage materials to prevent metal nitrate formation.

Table 1 Shuttle PRCS pilot-operated valve performance parameters

Parameter	Value
Weight, kg (lb)	<0.73 (1.6)
Operating pressure, MPa (psig)	
Range	1.2–2.4 (175–350)
Nominal	1.8 (264)
Operating temperature, °C (°F)	4–66 (40–150)
Coil voltage (dc, V)	
Range	21–32
Nominal	27
Coil resistance, Ω	21.3–22.5
Allowable mass flow rate, kg/s (lb/s)	
Oxidizer	>0.72 (1.59)
Fuel	>0.58 (1.27)
Main valve response time, ms	
Open	18–28
Close	12–21
Allowable in-field helium leakage, cm^3/h	
Oxidizer and fuel	>350[a]
Forward	Ambient 2.1 MPa (300 psig)
Forward	Ambient 0.034 MPa (5 psig)
Reverse	Ambient 0.069 MPa (10 psig)
Forward	Low temperature 0.034 MPa (5 psig)
Reverse	Low temperature 2.1 MPa (300 psig)

[a]During the time of publication of this paper, allowable in-field gaseous helium leakage rates for oxidizer valves were being reduced to 50 cm^3/h, except for the ambient 0.069 MPa (10 psig) reverse leakage rate (remained at >350 cm^3/h).

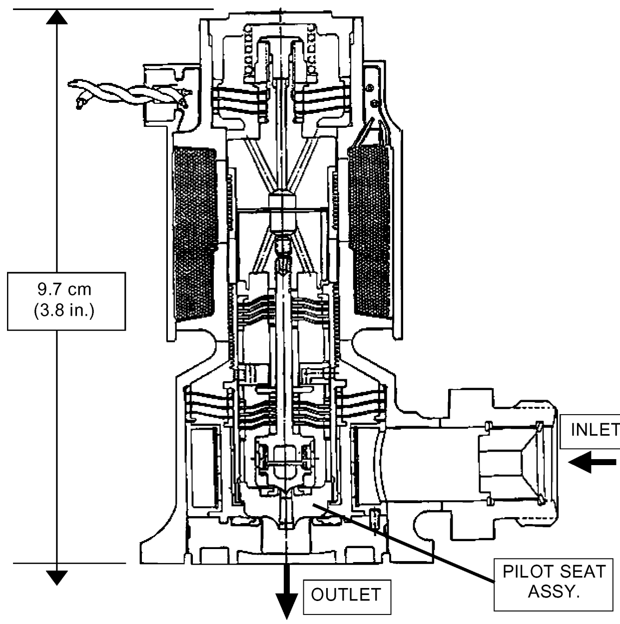

Fig. 1 Primary reaction control subsystem POV.

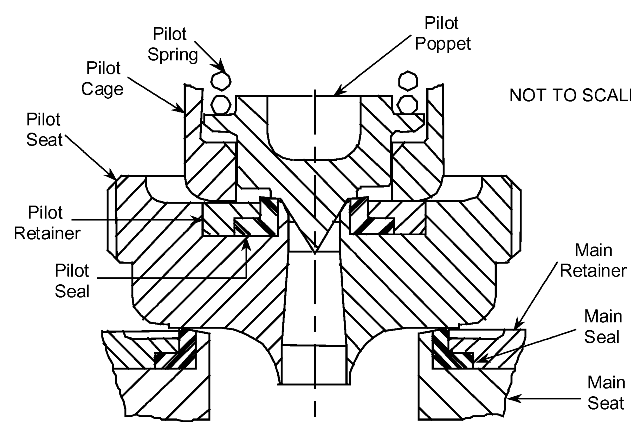

Fig. 2 Cross section of current POV configuration with poppet/seat interface.

Table 2 Comparison of PTFE materials used in POV and RPOV flight-configuration thruster hardware

Characteristic	POV	Initial RPOV	Final RPOV
Resin	Teflon-7A	Algoflon-E2[a]	Teflon-7A
Resin type	Non-free-flowing	Free-flowing	Non-free-flowing
Sintering	As-sintered	Presintered	As-sintered
Average particle size, μm	35 (powder)	300 (granular)	35 (powder)
Specification	MMS 2517	AMS 3658C	AMS 3660C
Product form	Molded rods	Extruded rods, tubes, and shapes	Molded rods, tubes, and shapes
Processing method	Compression molding	Extrusion	Compression molding
Tensile strength, MPa	20.6[b]	12.4[b] (18.6)[c]	20.7[b]
Elongation, %	300[b]	150[b] (297)[c]	200[b]
Specific gravity	2.14–2.20	2.14–2.20	2.14–2.20
Dimensional stability, %[d]			
Diameter	0.2	0.5	Not specified
Length	0.35	1.5	

[a]Also used in RPOV prototyping. [b]Minimum specification requirement. [c]Observed value in parentheses (exceeded requirement).
[d]Specimens heated to 175°C (353°F) for 4 h (MMS 2517), or 290°C (554°F) for 2 h (AMS 3658).

3) Increase propellant circulation around the pilot poppet to improve self-cleaning characteristics and minimize metal nitrate deposition and resulting stiction.

4) Minimize contact area between mating parts to reduce nitrate-related stiction.

To address these items, the following design features were incorporated into the RPOV: 1) a conical pilot-stage poppet/seat interface for improved sealing characteristics, 2) a new metal alloy with lower iron content and better nitric acid compatibility for the pilot poppet and seat, 3) a fluted poppet to reduce sliding contact with the cage and improve self-flushing, 4) an increased radial clearance between the poppet and cage to accommodate conical poppet self-centering and also to improve self-flushing, 5) additional flow holes in the poppet to reduce oxidizer stagnation, and 6) radial grooves on the bottom of the cage to reduce contact area with the seat and decrease potential nitrate-related stiction.

To preserve the force balance, opening/closing response, and vibration leakage characteristics of the POV, the outer diameter of the poppet-to-seal interface on the RPOV had to be maintained. In addition, the mass of each modified part had to match the mass of the part being replaced within 5–10%. Comparison of these and other POV and RPOV poppet/seat design parameters and cross-sectional geometries are shown in Table 3 and Fig. 3, respectively. One other change made to the RPOV design included adoption of a new procurement specification (AMS 3658C) for PTFE seal material. This specification became a major source of scrutiny after pilot seal microcracking and recession problems were observed during initial buildup of flight configuration RPOV hardware.

RPOV pilot seal microcracking and recession problems, coupled with concerns about ease of fabrication, led to other design modifications. Detail of the final RPOV design configuration is shown in Fig. 4. Changes incorporated into the final RPOV design included 1) decreasing the PTFE seal preform (preassembled PTFE pilot seal piece part) size to lessen seal squeeze (last column, last row in Table 3), 2) adopting tighter tolerances on critical pilot seal dimensions, while relaxing tolerances on less critical interfacing metallic part dimensions, and 3) selecting a new PTFE per specification AMS-3660C (for better mechanical property retention during hot-forming).

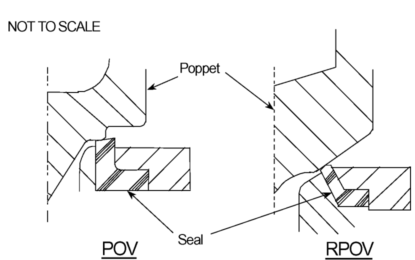

Fig. 3 POV (left) and RPOV (right) poppet/seat interface cross section.

Fabrication

To expedite RPOV fabrication, a hot-forming assembly procedure was devised. This procedure was thought to eliminate the need for exacting tolerances on the seal preform, maximize conformance to the seal cavity shape, and maximize thermal stability of the seal over the normal operating temperature range for PRCS thrusters. The hot-forming procedure consisted of the following main steps: 1) fabrication of an oversized PTFE seal preform; 2) installation of a loosely assembled preform, retainer, and seat into a hot-forming fixture; 3) oven heating of the entire assembly to 120–150°C (250–300°F) under load (at or above the heat deflection temperature of PTFE); and 4) removal of the heated assembly from the oven, followed by interference fitting (squeezing) of the PTFE seal preform while cooling.

Interference fitting during hot-forming was accomplished by applying torque incrementally to fixture bolts over a 10-min period. A guide pin, held in place by a weight, was used to prevent excessive extrusion of PTFE and minimize formation of voids in the seal cavity. After cooling to ambient temperature, the retainer was electron beam (EB) tack-welded to the seat with the retainer still mounted in the fixture under load. To avoid further extrusion of the pilot seal during fabrication, care was taken to minimize heat input during retainer welding. The excess PTFE was then machined off on a conventional lathe per recommended machining guidelines[7] to create the final seal profile.

A diagram of the hot-forming fixture used for fabrication of RPOV prototype parts is shown in Fig. 5. Manufacturing success during prototyping, as indicated by the ability to trim PTFE pilot seal to desired tolerances without microcracking or seal recession, provided confidence in the overall RPOV design and in the fabrication procedures. In addition to the earlier mentioned changes that were incorporated into the final RPOV design, several design modifications were made to the hot-forming fixture during the final RPOV design iteration. For example, the fixture was modified to support the pilot seat by the outer diameter threads and impart load to the new one-piece retainer while allowing line-of-sight access to the circumferential retainer/seat interface for EB welding. Photographs of successfully fabricated flight-configuration piece parts and a completed pilot seat assembly obtained during the final RPOV design iteration are shown in Figs. 6 and 7, respectively.

Table 3 Comparison of POV and RPOV poppet/seat design parameters[a]

Feature	POV	Initial RPOV	Final RPOV
Seal angle	Flat	Conical	Conical
New, deg	8	33	33
Used, deg	0	30	30
Retainer and seat materials	Custom 455 (MPS 0704/5)[b]	MP35N (AMS 5844D)	MP35N (AMS 5844D)
Seal material	PTFE Teflon (MMS 2517)[b]	PTFE Teflon (AMS 3658C)	PTFE Teflon (AMS 3660C)
Total pilot seat assembly mass, *g* measured	7.3	7.9	7.9
Poppet/seal contact area, mm^2[c]	3.0	2.6	2.6
Seal exit area, mm^2[d]	6.6	4.7	4.8
Entrapped seal volume, mm^3[e]	20.5	21.7	21.8
Seal proud height, mm[f]			
New	0.04	0.09	0.09
Estimated used	0.01	0.03	0.03
Seal squeeze, %[g]	Radial: 7.7 Axial: 6.3	33-deg off-radial: 23.8 Axial: 16.7	33-deg off-radial: 11.5 Axial: 10.4

[a]POV and RPOV values based on nominal piece part and seal trimming dimensions at ambient temperature.
[b]Specification from the original POV manufacturer, Kaiser Marquardt.
[c]Inner and outer edges of the poppet/pilot seal contact area are defined by the downstream metal seat edge adjacent to the pilot seal i.d. [= 2.83 mm (0.1115 in.)] and the poppet o.d. [= 3.51 mm (0.138 in.)], respectively.
[d]Exit area is the gap area between the downstream metal seat edge adjacent to the pilot seal i.d. [= 2.83 mm (0.1115 in.)] and the upstream metal retainer edge adjacent to the pilot seal o.d. [= 4.05 mm (0.1595 in.)].
[e]Volume the PTFE preform must occupy as dictated by metal seat and retainer tolerances and assuming complete bottoming out of the retainer in the seat.
[f]Proud height is the height of the i.d. edge of the pilot seal above the downstream metal seat.
[g]Excess seal preform volume relative to the smaller entrapped seal volume.

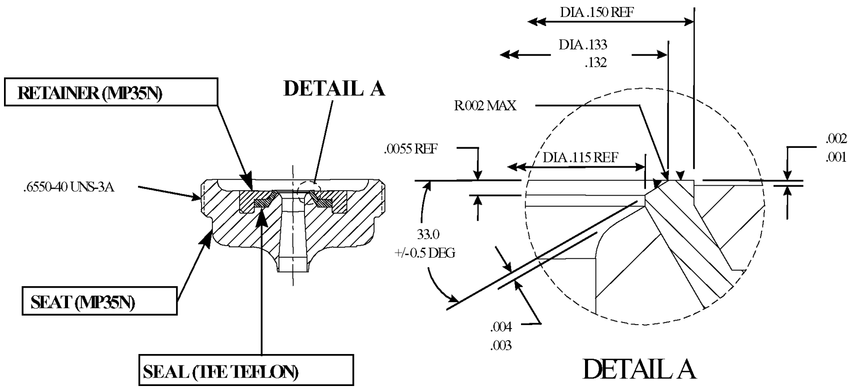

Fig. 4 Final RPOV seat assembly design configuration (all dimensions are in inches).

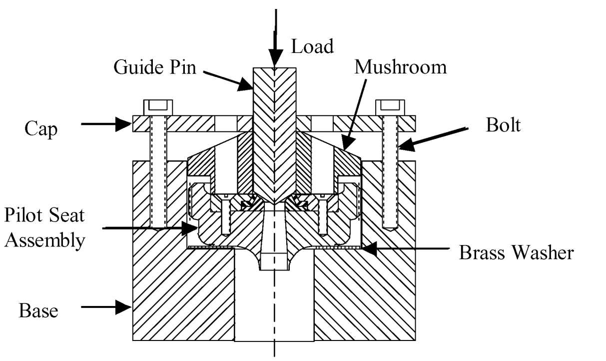

Fig. 5 Prototype RPOV hot-forming fixture; retainer screws used instead of EB weld.

Lessons Learned

Lesson 1: Prototyping

RPOV prototype hardware was built as a proof of concept. Accordingly, the prototype hardware was not flight representative. Although this design approach cleverly utilized existing parts and provided encouraging results regarding the manufacturing procedure, the reduced level of design rigor contributed to difficulties encountered later during buildup of flight-configuration hardware. In this regard, prototyping failed to reveal subtle, yet key, design, materials selection, and fabrication considerations unique to the flight configuration hardware. For example, it is now suspected that the two-piece retainer and screws used for securing the retainer to the seat inadvertently increased the mechanical compliance of the seal cavity. This reduced the amount of squeeze imparted to the pilot seal during prototyping. Problems such as seal microcracking, recession, and irreversible property changes associated with subjecting a presintered, free-flowing PTFE resin (A-E2) preform to high amounts of squeeze were, thus, not revealed. Also, the convenient use of uncontrolled PTFE grade during prototyping, rather than use of a carefully researched PTFE grade chosen on the basis of consultation with materials and processing experts, delayed selection of an optimum seal material. Finally, the lack of precise strain rate control during prototyping, along with design modifications made to the prototype hot-forming fixture, led to prototype and flight-configuration hardware variability.

Remedy: When complex hardware is developed, every effort should be made to maximize the likeness between prototype and subsequent design configurations. If the final design configuration is known, then prototype hardware should be built to approximate this configuration closely regardless of short-term cost or schedule implications. If the final design configuration is not known, then every effort should be made to minimize changes to a well-performing prototype configuration. Without careful consideration, minor design, materials, or fabrication changes can greatly affect conclusions drawn from prototyping and even invalidate the entire prototyping effort.

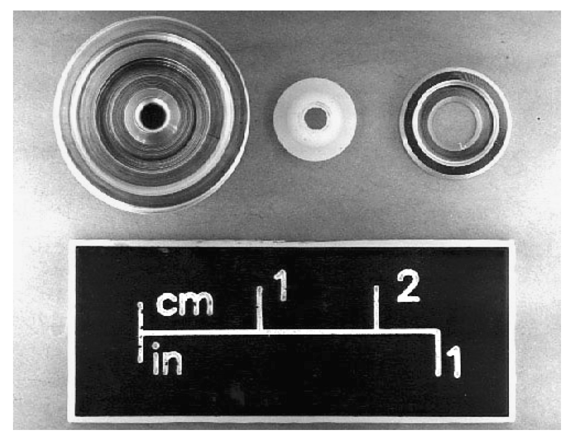

Fig. 6 RPOV seat assembly piece parts: left, seat; middle, preform; and right, retainer.

Fig. 7 Finished seat assembly obtained during final RPOV design iteration; note four EB spot welds located 90 deg about circumference of the retainer outer diameter.

Lesson 2: Machining of Miniature Seal Preforms

Machining of PTFE preforms was found to be a demanding art requiring special tooling, support equipment, and practice. First, machining PTFE parts to same tolerances shown in the original manufacturer's drawings [minimum/maximum range $= 25\ \mu$m (0.001 in.)] can be thwarted by excessive frictional heating during machining operations. For example, a 25-μm (0.001-in.) tolerance can be exceeded for ΔT (the frictional heating) greater than $\sim 30^\circ C^{-1}$ (60°F). {This assumes $\Delta T = L_0/(\alpha_{PTFE} \times \Delta L)$, where L_0 is the largest preform diameter [$=$ 6.4 mm (0.25 in.)], α_{PTFE} is the linear coefficient of thermal expansion (CTE) of PTFE [$= 1.24 \times 10^{-4\circ}C^{-1}$ $(6.9 \times 10^{-5\circ}F^{-1})$ for $T = 25$–$100^\circ C$ (77–212°F)], and ΔL is the calculated dimensional change.} Second, given the small size of the machined parts (Fig. 6), it was essential to see and measure accurately the article being machined.

This presents a challenge in that the resolution of most conventional measuring devices is only slightly better than the tolerances being controlled. Additional challenges arise during postmachining inspection. Many flaws that can damage the sealing surface and completely undermine sealing integrity, such as PTFE fibrils or metal slivers left over from piece part machining, can only be seen under 25–50× magnification. Third, proper cutting tool size, shape, material, cutting angle, nose radius, sharpening technique, cutting speed, and coolant were important considerations in obtaining desired tolerances and surface finish in PTFE articles. Whereas standard machining guidelines exist for generic PTFE articles, these procedures had to be refined due to the small size and exacting tolerances needed for the PTFE pilot seal preform. In summary, machining softgood piece parts to the desired tolerances and finish is a nontrivial undertaking that represents a significant expenditure in terms of both infrastructure and labor.

Remedy: Appropriate experience and tooling must be sought and ample time allocated for practice before viable seal preforms can be machined to the specified tolerances and finish. For example, machining of PTFE to close tolerances required spraying isopropyl alcohol directly on the PTFE during preform fabrication and final trimming. Accurate machining of small RPOV piece parts was further assisted by the use of a video microscope and monitor system with in-process measurement and inspection capability.

Note that the machining of piece parts, especially the PTFE pilot seal perform, but also including the mating metal seat and retainer, is but only skill that must be mastered before flight configuration pilot seat assemblies can be fabricated that are suitable for qualification phase testing. Equally important are interim inspections and measurements that must be performed before, during, and after the machining steps. It is no surprise that the original equipment manufacturer's pilot seat assembly fabrication process consisted of over 30 separate assembly, inspection, machining, and measurement steps. Many sequential pitfalls (which can be cumulative in effect) are, thus, encountered, each of which must successfully negotiated if suitable hardware is to be obtained.

Lesson 3: Pilot Seal Design Optimization

Seal Preform Size and Shape

The PTFE pilot seal preform and mating metal parts used in the fabrication of POV and RPOV pilot seat assemblies must be machined to precise tolerances. The PTFE preform dimensions by design must also be slightly larger than the dimensions of the corresponding metal cavity. This helps to ensure that a snug fit will exist between the plastic seal and surrounding metal in the finished POV or RPOV pilot seat assembly. If the amount of snugness is properly controlled, the adverse consequences PTFE cold flow during service can be effectively mitigated.[8] Cold flow, which is the tendency of thermoplastics such as PTFE to undergo low-temperature creep, whether due to applied external stress or internal stress relief, can even be exploited to replenish lost material and heal imperfections at the sealing interface during service, thus, enhancing sealing effectiveness and prolonging seal life.[9] If the PTFE seal preform is too small, gaps may form in the pilot seal cavity, which may cause the pilot seal to recede during service, ultimately leading to metal-to-metal contact and leakage. Conversely, if the PTFE seal preform is too large, the compressive yield point ε_c^Y of the PTFE can be exceeded during fabrication, resulting in irreversible plastic deformation and associated property loss.

Between 23 (73) and 100°C (212°F), ε_c^Y is essentially constant for PTFE: Calculated values of ε_c^Y $(=\sigma_c^Y/E_c)$ equal to 3.4 and 3.5%, respectively, are obtained. For PTFE, $\sigma_c^Y = 11.7$ (1700) and 4.8 MPa (700 psi), and $E_c = 345$ (50,000) and 138 MPa (20,000 psi) at 23 (73) and 100°C (212°F), respectively. Because the RPOV hot-forming temperatures [120–150°C (250–300°F)] used during part fabrication are only slightly higher than 100°C (212°F), but below the T_g of PTFE [= 160°C (320°F)], ε_c^Y is expected be of the order of 3.5% during hot-forming. Therefore, proper design of a RPOV or POV pilot seat assembly necessitates control of the size and shape (overfill) of the PTFE preform relative to the metal cavity dimensions to prevent introducing strains well in excess of ε_c^Y.

Surprisingly, the amount of overfill in the prototype or initial RPOV designs was found to be both excessive (exceeded ε_c^Y by a factor of ~5–8) and nonhomogeneous (17% axial vs 24% off-radial squeeze). By comparison, the amount of overfill in the POV was more homogeneous (6% axial vs 8% radial squeeze) and not as excessive (exceeded ε_c^Y by a factor of ~2). The RPOV overfill values were found to be close to POV ones (10% axial vs 11% off-radial squeeze, exceeded ε_c^Y by a factor of ~3, Table 3). Based on 20-year-old operational histories for the POV, exceeding ε_c^Y by a factor of ~2 does not appear to affect adversely pilot seal performance. By inference, the ~3% overfill used in the final RPOV design is probably acceptable. However, the ~5–8% overfill used in the prototype and initial RPOV designs, as will be shown later, was too excessive to permit fabrication of viable pilot seals.

Aside from the property losses introduced by exceeding ε_c^Y, using oversized preforms can have a more tangible drawback. If the as-fabricated pilot seat assembly made using an oversized preform has not been stress relieved (annealed) before final trimming, residual internal stress can manifest itself as unintended pilot seal extrusion later during service. This extrusion is expected to increase with the amount of overfill and may occur gradually under conditions of low use or storage, or more rapidly under conditions of thermal cycling, for example, during heat soakback after thruster firing. {Extrusion in this case would be driven by CTE mismatch. The CTE of PTFE (α_{PTFE}, given earlier) is an order of magnitude greater than that of the surrounding custom 455 stainless steel [$\alpha_{C455} \approx 1.06 \times 10^{-5}$°C^{-1} ($5.9 \times 10^{-6}$°F^{-1}) for $T = 21$–93°C (72–200°F)].}

Test data obtained on intentionally oversized, semitrapped PTFE specimens[2] support the contention that internal stress relief can contribute to extrusion. For example, the apparent CTE of the semitrapped PTFE was found to decrease with successive heatings, thus, reducing the effective CTE mismatch between the PTFE and surrounding metal. The decreasing effective thermal expansion mismatch between the PTFE and metal, coupled with simultaneous relief of internal stress within the PTFE, resulted in diminishing amounts of extrusion on each successive heating. Similar findings have been obtained on thermally cycled POV pilot seat assemblies.[10] In this study, the amount of pilot seal extrusion again was found to decrease with successive heatings. Although the amount of residual stress relief, and therefore, extrusion, was small, it was surprising that CTE mismatch-induced extrusion could still be detected after more than 10 years of storage of the as-fabricated part on the shelf.

The use of a nonhomogeneously oversized seal preform, as was the case in the prototype and initial RPOV designs, presents yet another drawback. Depending on the magnitude and direction of the resulting stress gradient within the pilot seal, either seal recession (radial stress greater than axial stress) or extrusion (axial stress greater than radial stress) can result. Therefore, to minimize any recession or extrusion, pilot seal preforms should be appropriately sized and residual internal stresses should be relieved by annealing, before final trimming and placing the part into service.

Exit Area/Volume Ratio

Extrusion of semitrapped seals is expected to increase with decreasing A_{exit} and increasing V_{cavity}. A differential expansion model for a PTFE pilot seal in a nominal POV configuration supports this contention.[2] In this model, pilot poppet/seal coverage was allowed to vary from 0 (no coverage) to 100% (complete coverage). Increasing poppet coverage (decreasing $A_{\mathrm{exit}}/V_{\mathrm{cavity}}$) led to greater predicted extrusion. In the case of the POV and final (flight configuration) RPOV designs, the final RPOV design has a lower $A_{\mathrm{exit}}/V_{\mathrm{cavity}}$ ratio [0.22 mm^{-1} (0.0087 in.$^{-1}$)] compared to the POV design [0.32 mm^{-1} (0.0126 in.$^{-1}$)], as determined using data given in Table 3. Therefore, the RPOV pilot seal is expected to be more prone to extrusion than the POV design. This contradicts prototype RPOV test data, which indicated that the prototype RPOV seal, despite having a similar $A_{\mathrm{exit}}/V_{\mathrm{cavity}}$ ratio compared to the flight configuration RPOV seal, was less prone to extrusion than a POV seal. However, this discrepancy could be attributed to 1) excessive compliance of the prototype RPOV seal cavity (resulting in lower seal squeeze in the prototype vs subsequent RPOV parts) and 2) use of

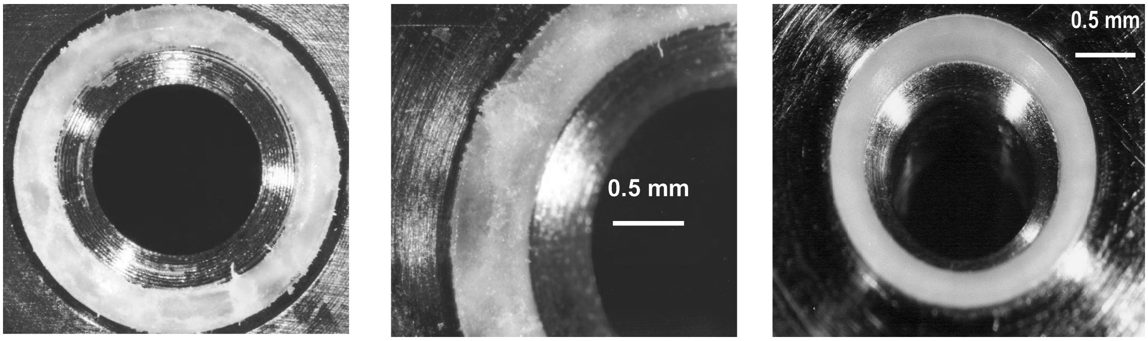

Fig. 8 Top view of initial RPOV seals made with Algoflon E-2 PTFE (left); overall splotchy appearance and fibrillation around seal i.d. and o.d. after trimming (middle); top view of a well-trimmed pilot seal fabricated from Teflon 7A PTFE (right).

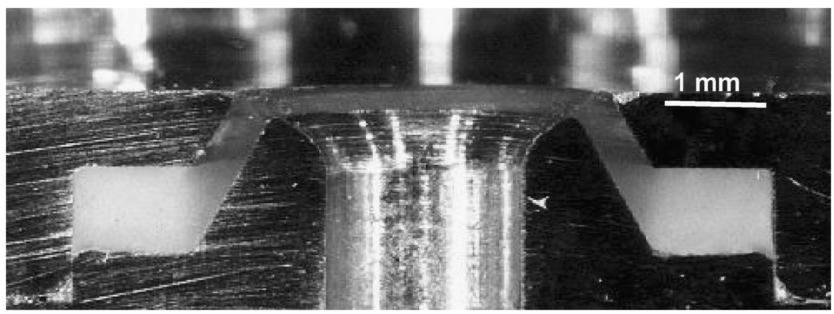

Fig. 9 Sectioned initial RPOV seal made with Algoflon E-2 PTFE, translucent and opaque regions.

an uncontrolled, presintered, free-flowing A-E2 resin grade during prototype seal fabrication.

Unoptimized Design Consequences

Plastics such as PTFE undergo flow at increasing temperatures, which if pronounced enough can result in molecular orientation and property anisotropy. In the case of RPOV fabrication, forced flow at too low of a fabrication temperature could exceed the ability of the material to flow and cause actual shearing apart of the molecules, leading to molecular weight reduction and associated property loss. Furthermore, the tendency of a resin to undergo undesirable property loss during fabrication could depend on the resin grade, as well as fabrication conditions.

Evidence of undesirable property loss was obtained during fabrication of initial RPOV seals (high squeeze) using the granular A-E2 resin. Trimmed AE-2 seals had a mottled, splotchy appearance in areas where the greatest amount of (off-radial) seal squeeze had occurred. This material was especially prone to fracture and fibrillation during trimming (Fig. 8). Subsequent sectioning of the pilot seat assembly revealed A-E2 had a translucent appearance in the regions of highest interference fit (∼24% squeeze) and a normal opaque appearance in the regions of lowest interference fit (∼17% squeeze) (Fig. 9).

Inspection of the PTFE phase diagram shows the presence of a crystalline phase disordering transition involving helical untwisting[11] near the RPOV fabrication temperature (dashed line, Fig. 10). The temperature of this transition decreases with increasing pressure (or stress). However, the stress produced by a 24% interference fit, as estimated from American Society for Testing and Materials D 695[12] stress/strain data,[7] would only be about 13.8 MPa (2000 psi) at 100°C (212°F), falling to 8.3 MPa (1200 psi) at 204°C (400°F). Although these stresses are relatively small, they could be high enough to cause crystalline disordering at temperatures in the vicinity of the hot-forming temperature used [120°C (250°F)].

Another explanation for the formation of translucent PTFE could be shearing apart or reduction in size of PTFE spherulites. (Spherulites are crystalline domains typically found in semicrystalline thermoplastics such as PTFE, which if larger than the wavelength of visible light will cause the light to be scattered, thus, giving the material an opaque appearance.) This scenario is plausible considering the overstress applied to the seal preforms during

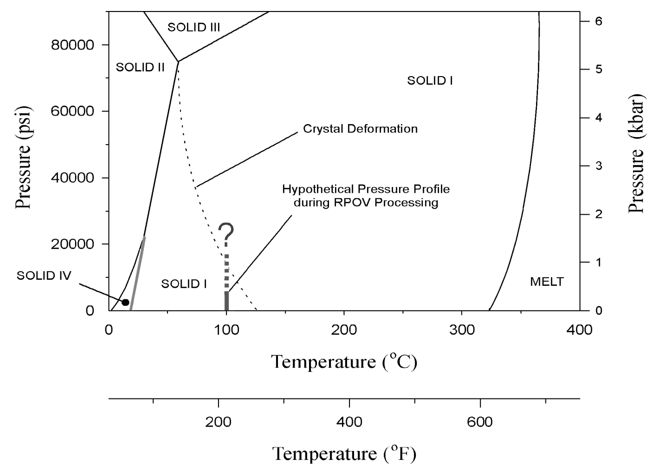

Fig. 10 PTFE phase diagram: – – –, location of a crystalline phase disordering transition in the vicinity of the 120°C (250°F) RPOV fabrication temperature.

fabrication. Data further support this contention. For example, increasing compressive strain (percent squeeze) was found to cause a continuous drop in the Shore A® (Instron Corporation, Canton, Massachusetts) durometer hardness of compression-molded PTFE coupons made from T-7A procured per AMS 3660C (Fig. 11). For example, a 5% hardness drop was noted after subjecting a coupon to 25% strain. Hardness reductions in semicrystalline thermoplastics such as PTFE are generally regarded as indicative of irreversible deformation modes within crystalline lamellas involving chain slip and tilt at lower strains, followed by lamellar shear and crystal destruction at larger strains (J. Peterlin as cited in Ref. 13). The drop in hardness observed in Fig. 11 is, therefore, consistent with the notion of irreversible crystal deformation during the fabrication culminating in formation of translucent PTFE.

Remedy

When PTFE is used in design, its tendency to undergo cold flow during service must be factored into the design. Also, whereas a positive interference fit is necessary to avoid seal recession and gap formation, the interference fit should be at or slightly above the

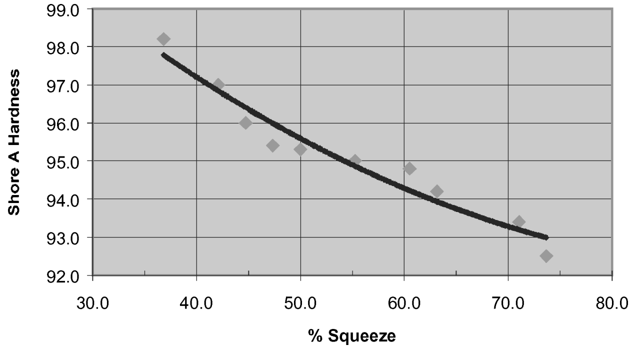

Fig. 11 Effect of increasing percent squeeze (platen pressure) on the Shore A durometer hardness of compression-molded Teflon-7A PTFE.

compressive yield point range of PTFE to ensure snugness of fit, while minimizing irreversible mechanical property loss. Care must also be taken to minimize the internal stress gradient across the semitrapped seal, thus, minimizing unintended extrusion or recession later in service.

Buildup of high levels of internal stress could also be minimized by using a slower strain rate during tightening down on the retainer during hot-forming, or by postfabrication annealing. Whereas the possible benefits of strain rate control or annealing were not investigated in this study during RPOV buildup, or are well understood for POV hardware, such changes could ultimately improve the reproducibility and performance of semitrapped pilot seals.

Lesson 4: PTFE Material Selection

Presintered, Non-Free-Flowing, or Free-Flowing PTFE

There are three principle grades of PTFE granular molding powders: 1) presintered, free-flowing powders for extrusion molding (such as A-E2), 2) as-sintered, non-free-flowing powders for compression molding (such as T-7A), and 3) as-sintered, free-flowing powders, also for compression molding. Unfortunately, there is little commercially available resin selection design assistance for specific applications such as thruster valve seals.

Ram-extruded, free-flowing PTFE (A-E2) and compression-molded, non-free-flowing PTFE (T-7A) were hard to distinguish by most laboratory tests; nevertheless, each exhibited unique physical and mechanical properties that were pivotal in fabricating viable vs nonviable parts. Unfortunately, existing procurement specifications either do not clearly or meaningfully distinguish between available candidate resins. To aggravate matters, meaningful properties such as deformation under load (creep), retention of properties at operational thruster temperatures, and resistance to propellants are not covered in specifications.

Judicious material selection can, therefore, hinge on identifying and performing more meaningful tests that can distinguish between candidate resins. Such data can be used to help the design engineer to determine if key performance indicators not covered in existing specifications are satisfied. For example, a squeeze test was devised in this study that allowed A-E2 specimens to be distinguished from T-7A specimens (Fig. 12b). In this test, PTFE specimens were heated up to 120°C (250°F) to mimic the RPOV fabrication temperature. One face of the squeeze fixture was inclined, which allowed a compressive strain gradient ranging from 15 to 90% to be imparted over the specimen area. Results showed that specimens made from A-E2 produced a lower strength PTFE that was more susceptible to fracturing (Fig. 12b, bottom). Because A-E2 consists of coarse, agglomerated particles, fracturing was attributed to adhesive failure along particle boundaries. By comparison, a specimen made from T-7A gradually transitioned from fully opaque to translucent material without any evidence of fracturing or splotchiness (Fig. 12b, top).

Remedy

The criticality of understanding unique PTFE properties that derive from subtle resin grade differences cannot be underestimated. Comprehensive research and testing is needed before fabricating parts for demanding operational environments. Switching from a ram-extruded to a compression-molded PTFE resin grade allowed fabrication of viable seals suitable for valve-level qualification testing.[3] Proper resin selection also was found to compensate partially for an unoptimized seal design and fabrication. The squeeze test was ultimately found to be useful in screening candidate materials. In retrospect, given the nature of the hot-forming assembly process being used, the material with the highest resistance to compressive fracturing should have been chosen initially.

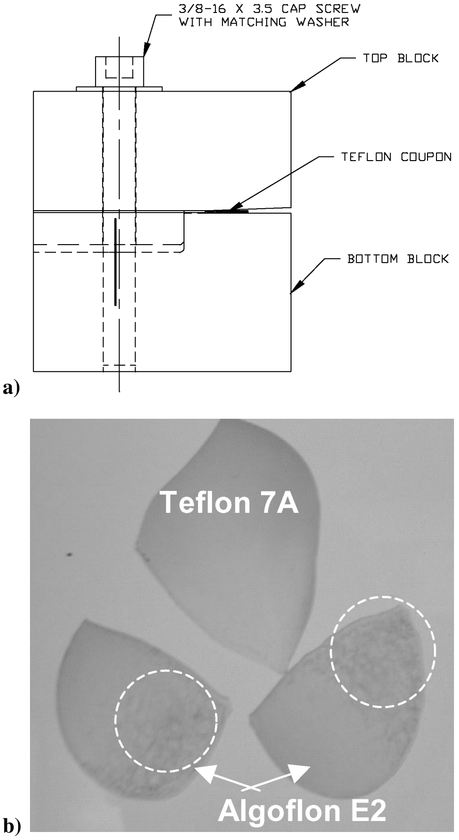

Fig. 12 Material distinguishment: a) squeeze test fixture used and b) Teflon-7A (top) and Algoflon-E2 (bottom) PTFE specimens (notice fracturing within in the Algoflon-E2 specimens).

Current POV pilot seat assembly procedures employ a cryofitting technique, rather than the hot-forming technique described herein. In retrospect, the advantages attributed initially to hot-forming (expedite fabrication, eliminate need for exacting tolerances, maximize thermal stability of the seal) were not fully realized. In fact, hot-forming may have brought resin grade and property issues into play that would have otherwise been unnoticed.

Lesson 5: RPOV Seal Dimensional Instability

Seal Extrusion

Seal extrusion caused by CTE mismatch between adjacent PTFE and metal parts in the POV or RPOV, and possibly aggravated by 1) excessive internal stress, 2) internal stress gradients, 3) thermal cycling during fabrication, 4) retainer welding, or 5) heat soakback after thruster firing, must be anticipated and minimized. For example, experimental data on semitrapped PTFE and modified PTFE specimens simulating a POV seal configuration show that extrusion 1) is incremental, 2) is not quantitatively recoverable (some nonrecoverable extrusion after each heat cycle), 3) increases with the size of the thermal excursion, 4) decreases with successive thermal cycling, and 5) is accompanied by gap formation in the seal cavity.[2,14] Heat, energy, and gas producing events during ground turnaround caused by undesirable reaction of oxidizer vapor in or near fuel valve pilot seals are now thought to play a key contributing role in extrusion (perhaps more so than CTE mismatch).[10] These factors must be considered in the design, material selection, and fabrication of a thruster valve pilot seat assembly.

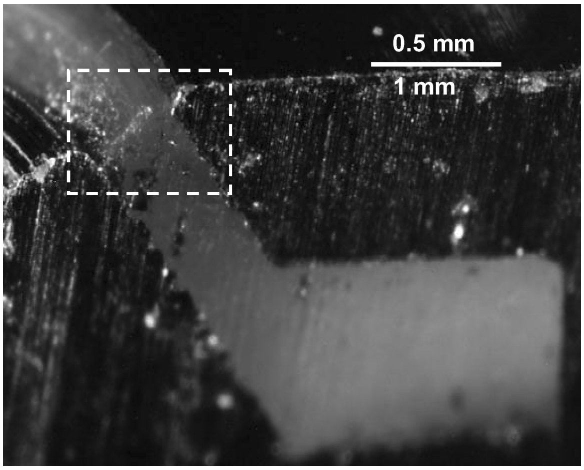

Fig. 13 Sectioned RPOV pilot seat assembly, seal recession (boxed region) after valve-level acceptance testing; seal has receded into the cavity by approximately 0.050 mm (0.002 in.).

Seal Recession

Seal recession is characterized by a nonuniform loss of seal proud height around the circumference of the seal (Fig. 13). Because recession deprives the seal interface of material, leakage can result. Similar to the extrusion case, the recession shown in Fig. 13 was accompanied by gap formation within the seal cavity. Recession arises from negative internal stress during differential thermal contraction of the seal relative to the surrounding metal. Although recession was observed after valve-level acceptance testing of RPOVs, it is at least conceivable that recession could also occur immediately after RPOV fabrication due to overheating or using too small of a preform.

Remedy

Because the CTEs of plastics and metals differ by an order of magnitude, preventing unwanted seal extrusion and recession entails implementation of appropriate design and fabrication vs material remedies. More effective seal entrapment design strategies could be implemented, for example, using grooved or barbed retainer surfaces, or different seal cavity entrapment geometries. Alternatively, the time-at-temperature during the seal's service lifetime could be minimized, or deleterious exposure of fuel valve pilot seals to oxidizer vapor could be avoided. Unwanted seal extrusion or recession could also be prevented by optimal seal preform geometry, lower process temperatures, and lower stresses and strain rates during the seat assembly process.

Lesson 6: Seal Property Modification During Service

PTFE has a high affinity for oxidizer. Various researchers have reported $\sim$5% (v/v) mass uptake after a prolonged 71°C (160°F) hydrostatic immersion in oxidizer.[2,14] The corresponding effect of fuel on PTFE properties is by comparison negligible.[2] In addition to a mass increase, some of the property changes observed after oxidizer exposure include swelling,[2] softening,[2,9] and reduction of density and crystallinity.[9]

Remedy: Immersion studies simulating operational exposure conditions should be performed to determine the extent of real-time property modification attributable to prolonged propellant exposure under operational conditions. For example, little is known about the potentially antagonistic effect of temperature and oxidizer exposure on the compressive yield behavior of pilot seals. Also, little is known about the forced uptake on fuel (monomethylhydrazine) by PTFE at nominal propellant fed pressures. To better understand the performance of PTFE in PRCS thruster sealing applications, acquiring such data would be highly beneficial.

Conclusions

Redesign of the problematic shuttle primary reaction control subsystem POV pilot seat assembly resulted in greater difficulty than anticipated. For example, the desire to obviate the requirement for precise seal design tolerances using a hot-forming approach was countered by the need to minimize excessive stress buildup and gradients within the seal. Use of an unoptimized resin and process conditions lead to many undesirable artifacts in fabricated pilot seals such as microcracking, reduction in seal hardness, and seal recession. Many of the have shortcomings described herein could have been prevented or mitigated by 1) searching out and obtaining nonproprietary design help, 2) being less reliant on generic material specifications ill-suited for rigorous aerospace applications, 3) using or generating more comprehensive technical data on candidate PTFE resins to provide a basis for judicious material selection, and 4) obtaining better knowledge of existing fabrication procedures and associated shortcomings.

Only once these design, material selection, and fabrication pitfalls were fully understood, could steps be taken to fabricate viable thruster valve pilots seals (Fig. 8, right).

Acknowledgments

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I. Vas
Associate Editor