Space Shuttle Orbiter Atlantis Liquid Oxygen Pre-Valve Detent Roller Cracking Investigation

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Abstract

During routine inspections of the Space Shuttle's Main Propulsion System Liquid Oxygen (LO_2) pre-valve, the mechanism provided to maintain the valve in the open position was found cracked. The mechanism is a Vespel roller held against the valve visor by a stack of Belleville springs. The roller has been found cracked 3 times. All three instances were in the same valve in the same location. There are 6 pre-valves on each orbiter, and only one has exhibited this problem. Every-flight inspections were instituted and the rollers were found to be cracked after only one flight. Engineers at Marshall Space Flight Center, Johnson Space Center, and Kennedy Space Center worked together to determine a solution. There were several possible contributors to the failure: a misaligned visor, an out-of-specification edge with a sharp radius, an out-of-specification tolerance stack up of a Belleville spring stack that caused un-predicted loads on the Vespel SP-21 roller, and a dimple machined into the side of the roller to indicate LO_2 compatibility that created a stress riser. The detent assembly was removed and replaced with parts that were on the low side of the tolerance stack up to eliminate the potential for high loads on the detent roller. After one flight, the roller was inspected and showed fewer signs of wear and no cracks.

Introduction

NASA's Space Shuttle is propelled into orbit by two solid rocket boosters and three Space Shuttle Main Engines (SSMEs). The SSMEs are liquid rocket engines that use liquid oxygen and liquid hydrogen as propellant. The propellant is stored in the non-reusable external tank. During loading, the propellants flow through the orbiter by way of the fill and drain system on the Main Propulsion System. The propellants are loaded in this manner in order to cool down the various Main Propulsion System fluid components and to chill the engines. This prevents gas ingestion by the engines during ignition.

The Main Propulsion System contains various sub-systems including the feed system. The feed system allows flow of oxidizer and propellant from the external tank to the three SSME's. After the feed system manifold, there are three pre-valves that are used for isolation of the propellant supply from the SSME's. These pre-valves are used to prevent catastrophic failures of the oxidizer turbo pump during nominal engine shutdown as well as during a contingency situation when engine isolation is necessary. Because of these important tasks, the pre-valves are inspected and tested routinely.

Valve Function

Each Space Shuttle Main Engine has two 30.5-cm (12-inch) diameter propellant isolation valves. One valve is in the liquid hydrogen system and the other in the liquid oxygen (LO_2) system. They are referred to as pre-valves and are located in the Main Propulsion System. The pre-valves are used during all phases of the shuttle operation: fill and drain of the external tank, ascent, and in contingency situations. The primary purpose of the pre-valves is to stop the flow of propellant to the SSME's in the case of an engine failure or shutdown. The restriction of flow reduces the likelihood of an uncontained fire in the aft compartment or engine. The LO_2 pre-valves also serve a critical purpose during Main Engine Cut Off (MECO). During MECO, helium is injected from the SSME pogo accumulator into the area upstream of the high-pressure oxidizer turbo pump (HPOT). This maintains the proper pressure for shutdown of the HPOT and allows for safe engine shutdown. The pre-valves close, providing the sealing force to maintain

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the pressure and limit the volume that must be pressurized. The valves also allow the recirculation pumps to operate to chill the engines prior to launch. In order to prevent overpressure of the feedlines, the valve contains a reverse flow relief valve and a visor liftoff mechanism.

The pre-valves are pneumatically actuated, bi-stable, two-position valves. The valve has a half-moon-shaped inconel visor that seals against a Kel-F seat in the closed position. A photo of the valve between the open and closed positions is shown in Figure 1. To open the valve, helium is supplied to an actuator that rotates the visor out of the propellant flow path. When the valve opens, two Belleville spring-loaded mechanisms hold a small roller in detent grooves on each side of the visor to ensure the visor remains in the fully open position. These detent mechanisms serve as a mechanical latch to hold the valve in the open position to prevent an unwanted closure of the valve during engine operation. Because the valve is bi-stable, the detent mechanisms add redundancy to the valve. Helium is again supplied to the opposite side of the valve actuator piston to close the valve.

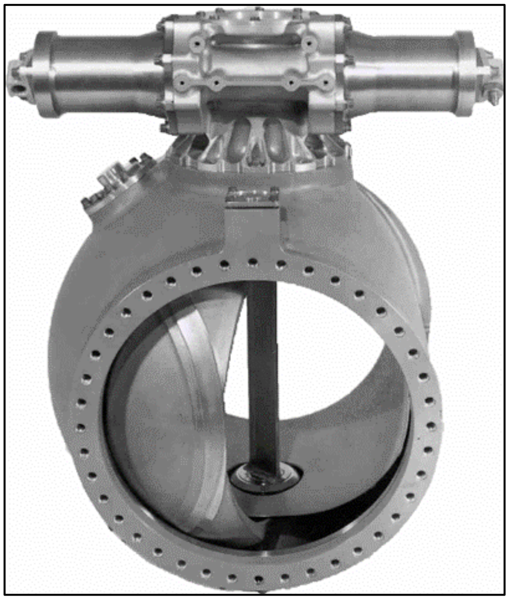


Figure 1: Space Shuttle Main Propulsion System Pre-Valve

Pre-valve Detent Mechanism Description

The detent mechanisms are composed of several piece parts as shown in the cross sectional and exploded views in Figures 2 and 3. The assembly contains a roller, pin, and follower that allow the mechanism to translate across the visor. The assembly also contains a stack of Belleville springs and spacers. The springs allow for vertical movement of the roller. The spacers protect the springs from rubbing on one another and allow the springs to invert.

The detent roller is manufactured from LO_2/LH_2 compatible Vespel SP-21. As the valve opens, the part of the visor known as the ramp comes into contact with the roller compressing the Belleville spring stack in the detent mechanism. The roller travels along the ramp to the detent groove, shown in Figure 4. Figure 5 shows the valve in the open position with the roller locked in the detent groove. Rotation of the visor itself is controlled by mechanical stops in the actuator that do not allow the visor to rotate more than 90 degrees. The stop also prevents the roller from rolling through the groove and out the other side. As the roller moves up the ramp, the follower also moves up. This upward motion compresses the Belleville spring stack. As the stack is compressed, the spacers slide within the detent cap guiding the entire stack’s motion. They also keep the four Bellevilles from contacting each other as each is compressed so that they can move beyond the point where they invert. The top spacer contacts a lip on the cap and transmits the force of stack deflection through the cap and into the seven bolts holding the mechanism within the valve body. The cap retains a static spring energized seal in the valve body that prevents propellant leakage into the aft compartment of the Orbiter. When the valve is commanded closed, the actuation force generated overcomes the force generated by the roller in the groove and compresses the spring stack until the roller is forced out of the detent groove. The roller then rolls down the visor ramp until the two parts are no longer in contact with each other. In the closed position, the detent Belleville's are only compressed to their installation height and the roller and follower hang inside the valve. The follower has a large land that contacts the retainer to hold it in place. The retainer serves multiple purposes: it prevents the follower and spring stack from falling into the valve and ensures the spring stack is compressed to the installation height before coming into contact with the visor, the retainer is keyed within the cap to prevent the mechanism from being installed in a manner where the roller and detent groove would not line up, and the retainer prevents the follower from pivoting or rotating as the roller moves up the visor ramp.

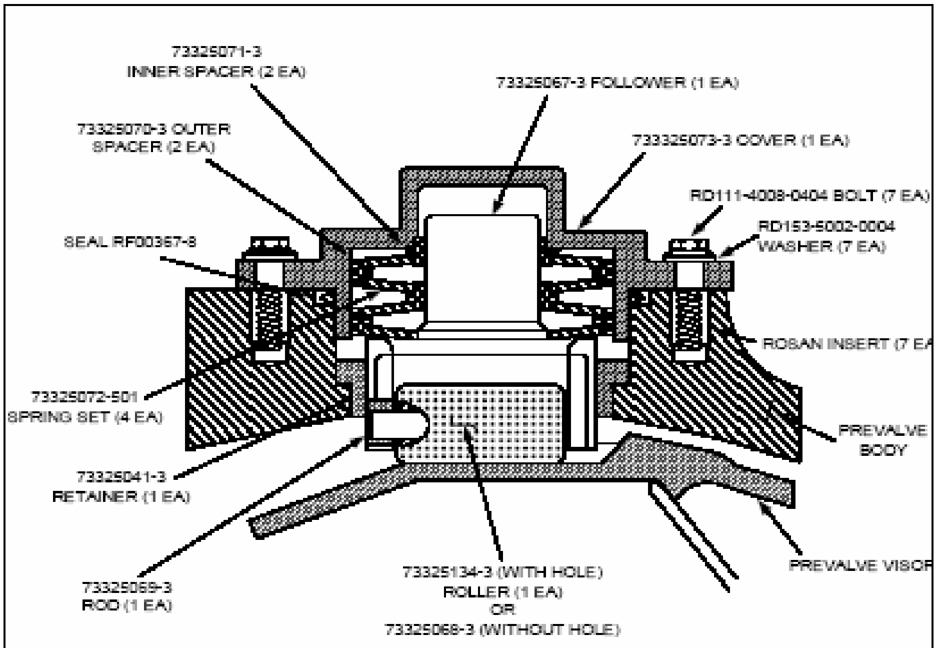


Figure 2: Cross-section of the detent mechanism

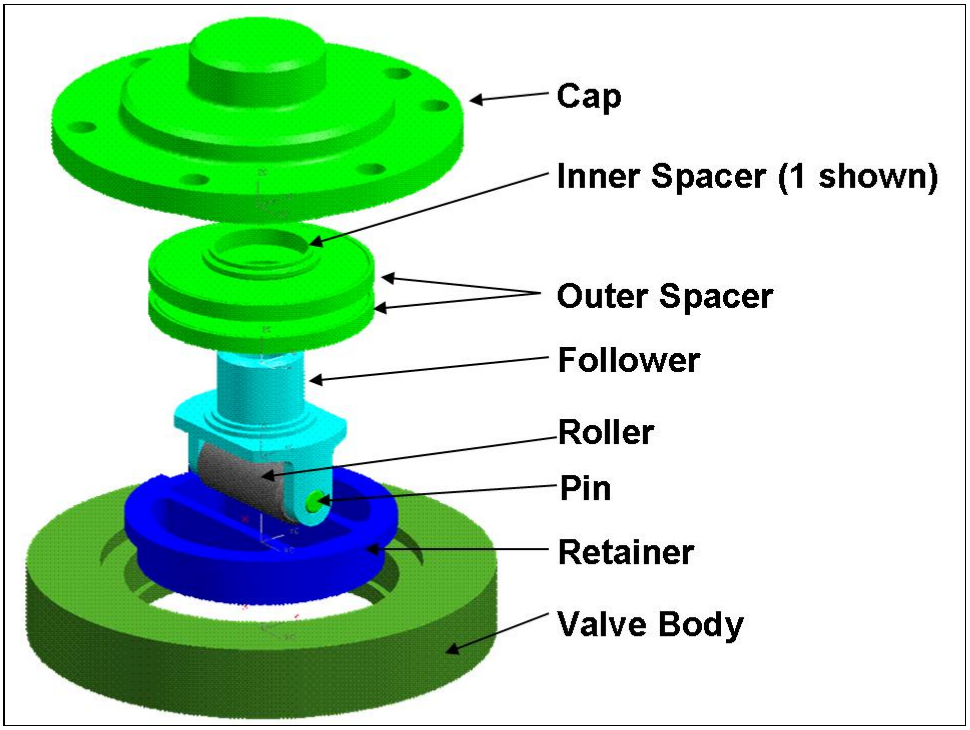


Figure 3: Exploded view of the different detent mechanism's piece parts

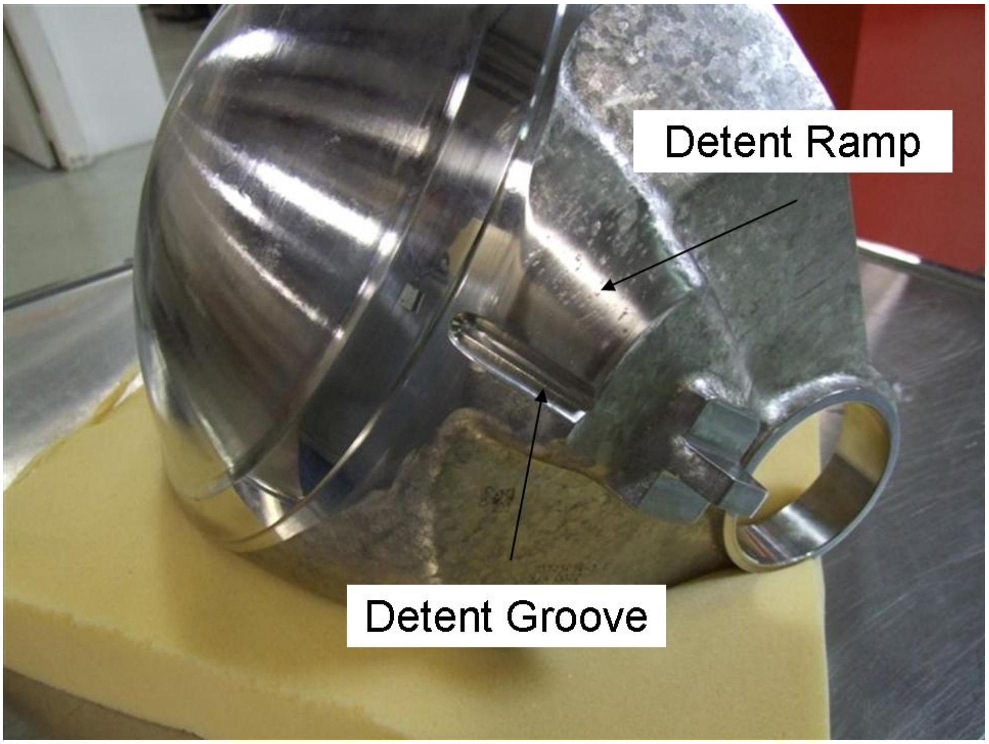


Figure 4: Pre-valve Visor

Figure 5: Roller locked in the detent grove when the valve is in the open position

Detent Mechanism Inspections

During an inspection of OV-104 (Atlantis) after the vehicle's second flight, one of the detent rollers in the engine 3 LO_2 pre-valve was found to have a crack through the full thickness and down one third the length of the part. The root cause of the crack was not found and the crack was dismissed as a one-time occurrence. However, as part of the forward plan, the requirement to inspect each roller during every vehicle's Orbiter Maintenance Down Period (OMDP) was instituted. During every OMDP, all six LO_2 and LH_2 detent mechanisms are removed from the pre-valves and inspected for wear or damage. Each roller typically shows a washboard pattern around its circumference that is considered nominal wear. This pattern is due to the large visor swinging and contacting the motionless roller. Because the surface of the visor is relatively rough and the visor moves at a fast rate, it is suspected that the roller does not roll smoothly across the visor. The slipping of the roller may contribute to the "wash board" wear marks that are typically seen around the roller.

As the Belleville spring is compressed, the roller is forced against the retainer that results in wear on the roller. Also, there are typically black indications on the retainer where this contact takes place. The black marks indicate deposits of Vespel material were transferred from the roller surface to the retainer.

Some rollers within the fleet are specially machined to have a smaller diameter in specific locations. The purpose of this process is to reduce the effect of rough or high spots on that specific valve's visor. During inspections after the initial flights of the OV-103 and OV-104, several rollers in the LH_2 and LO_2 systems were found with rough gouges at specific distances along their lengths. Borescope and visual inspections concluded these instances of damage were due to wear associated with the high spots on each visor. Two rollers showing this type of damage are shown in Figure 6. Examples of specially machined rollers with gaps to avoid a high spot on a discrepant visor are shown in Figure 7.

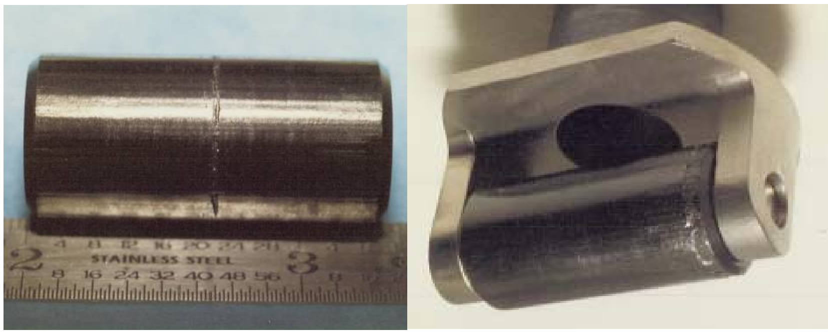


Figure 6: Rollers Exhibiting Wear due to High or Rough Spots on the Visor

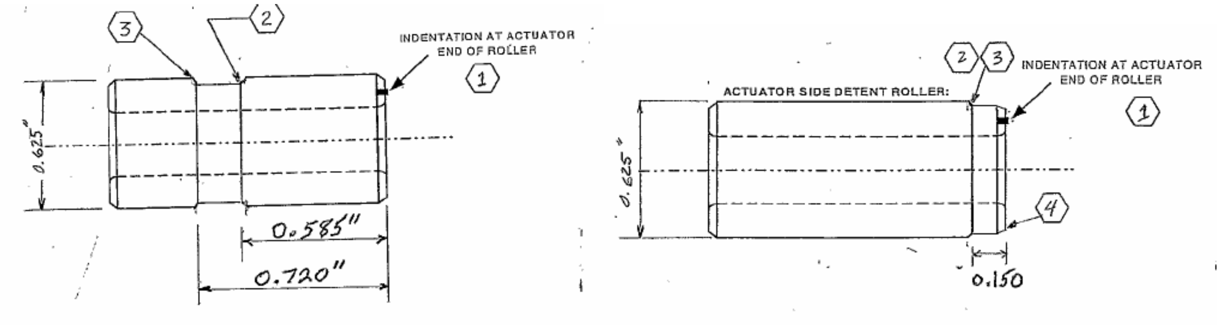


Figure 7: Drawings showing how these rollers are machined to avoid discrepant areas on valve visors

In addition to roller wear, the retainers also show signs of wear due to contact from the side of the follower. Deposits of the retainer material have been found on the pin and follower, which further supports the theory that the retainer is being damaged by these components. The cap also shows signs of wear due to the sliding contact of the four spring spacers. Example of nominal wear associated with spacer travel in the cap can be seen in Figure 8. All parts of the assembly are inspected thoroughly and replaced if the wear is considered significant. Minor wear to metal parts may be treated with Chem-film which is an acceptable practice for Shuttle LO_2 and LH_2 systems.

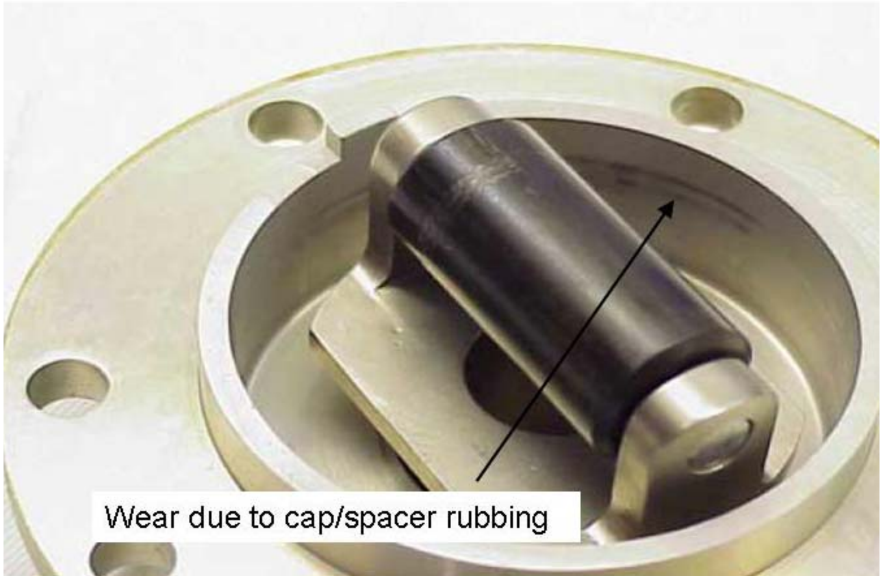


Figure 8: Cap showing signs of nominal wear due to spacer rubbing

Cracked Roller Anomaly

To date, three cracked rollers have been found through inspection. All 3 rollers were in the OV-104 Engine 3 LO_2 pre-valve. The first cracked roller was found after the second flight of OV-104, which led to the inspections discussed above. During OMDP for OV-104 after Flight 26, the second cracked roller was discovered. Following this investigation, every-flight inspections were instituted for the specific Engine 3 LO_2 pre-valve. During these inspections, the third cracked roller was discovered. Unlike the prior two cracked rollers, this roller cracked after only one flight. This raised concerns that a cracked roller that remains in service may degrade further and cause a serious failure in the LO_2 system.

A cracked roller may liberate debris. This debris should be captured by the pre-valve screen, which is a 1000-micron screen downstream of the pre-valve to prevent contamination from entering the engine.

Another failure mode is that if the roller completely fails and the metal follower comes in contact with the pre-valve visor, an ignition source would be created in the highly volatile LO_2 environment.

After the second failure was discovered, two likely causes were identified: roller material LO_2 compatibility testing marks, and detent groove leading edge sharpness. Before a soft good or non-metallic material is used in Space Shuttle LO_2 systems, each batch of the material must be compatibility tested. The Vespel SP21 used for the roller requires this testing. To ensure that rollers that aren't batch tested are not installed in the vehicle, a small dimple is machined into the end of the roller to indicate that the material successfully completed the required testing. The depth and diameter of the dimple are drawing controlled. The mark is to be no more than 0.76-mm (0.030-inch) deep and 1.57 mm (0.062 inch) in diameter. It was noted that the crack observed on the second and third cracked rollers initiated at the dimple and propagated through the thickness of the roller. The dimple was identified as a stress riser and a contributor to the cracked rollers. However, it was also noted that the first cracked roller did not have a dimple, so there is likely an additional cause.

Testing was performed to verify that a roller with a dimple has reduced fracture toughness. However, during this testing, the loads required to crack a roller were less than the estimated loads imparted by the Belleville spring stack in a nominal assembly. This information prompted further investigation after the third roller was found cracked. The original intent of the testing was only to prove that the dimple did affect the fracture toughness of the roller. The testing was performed at ambient conditions. The load required to crack a dimple-less roller was twice that of the load required to crack a roller with a dimple.

Molds of the visor detent groove were made so that measurements of the key dimensions of the visor could be taken. It was determined that the radius of the lip of the leading edge of the detent groove was sharper for this particular valve visor than drawings for the part allowed. The edge radius underwent a grinding and polishing process with the valve installed on the vehicle. Prior to machining, the radius was found to vary between 0.13 to 0.51 mm (0.005 to 0.020 inch) at various points along the length of the detent groove. The drawing requirement for this radius was 0.38 to 0.76 mm (0.015 to 0.030 inch). After the procedure, the sharpest dimension found along the length of the detent leading edge was 0.48 mm (0.019 inch). The polishing process was performed between the second and third rollers.

It was also noted from the mold impressions that the one end (labeled as "5" in Figure 9) of the leading edge was slightly higher than the other. This resulted in an unparallelism between the roller and visor interface. This unparallelism resulted in one side of the leading edge being approximately 0.64 mm (0.025 inch) higher than the other. This meant that one end, the horseshoe shaped end, compressed the detent roller more than the open end. All three cracks initiated on the end corresponding to the higher compression.

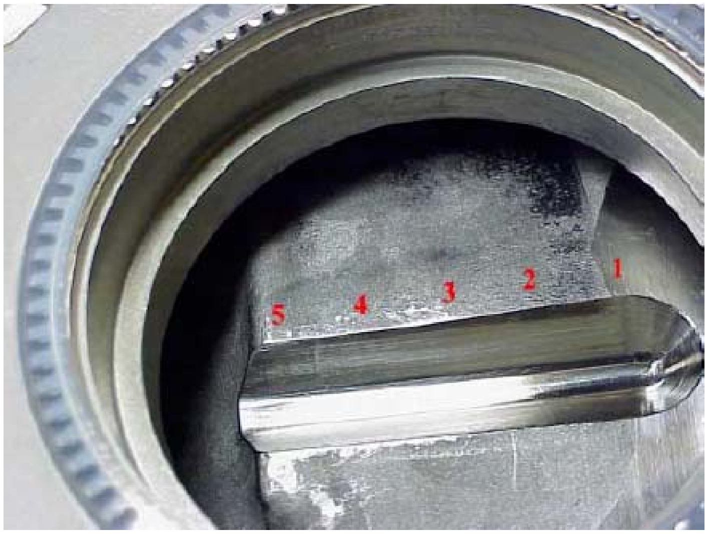


Figure 9: Pre-valve Visor Detent Groove

Rationale to fly after finding the second cracked roller was based primarily on the conclusion that the sharp leading edge of the detent groove was the root cause of the cracking. However, after the detent groove leading edge was returned to print, the third roller cracked after only one flight. The second and third cracked rollers can be seen in Figure 10. In each case, the crack was observed to run through the LO_2 compatibility testing mark and completely through the thickness of the roller. This can be seen in Figure 11.

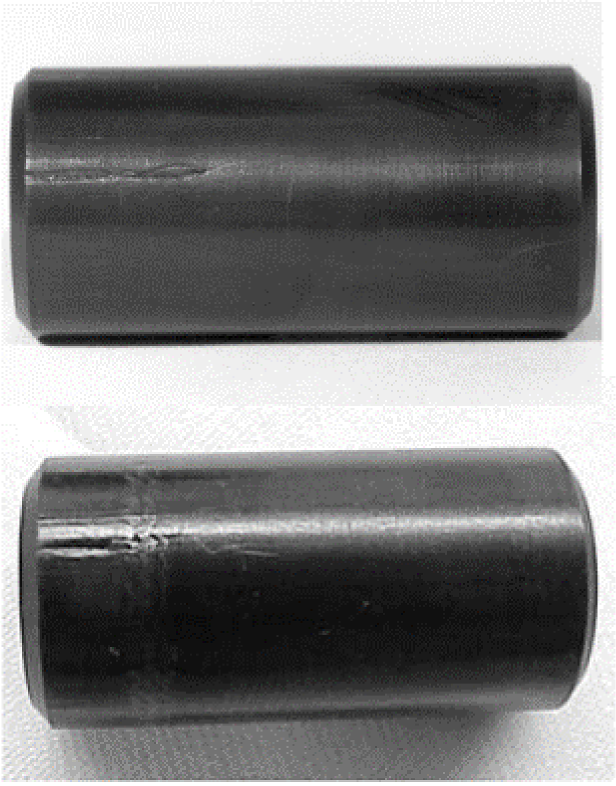


Figure 10: The second and third cracked rollers

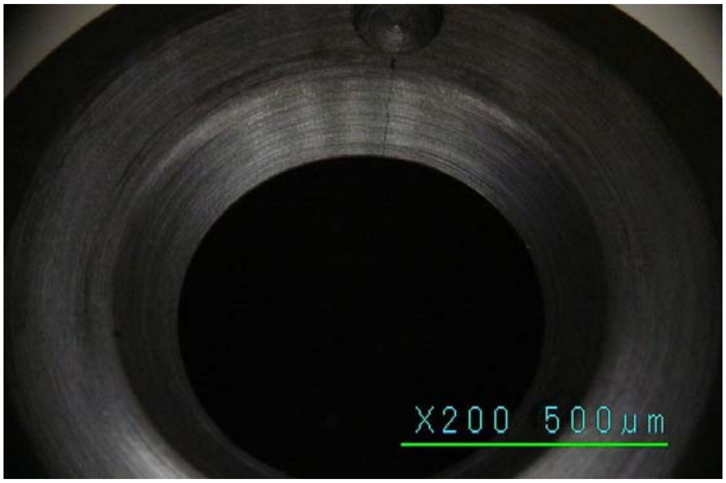
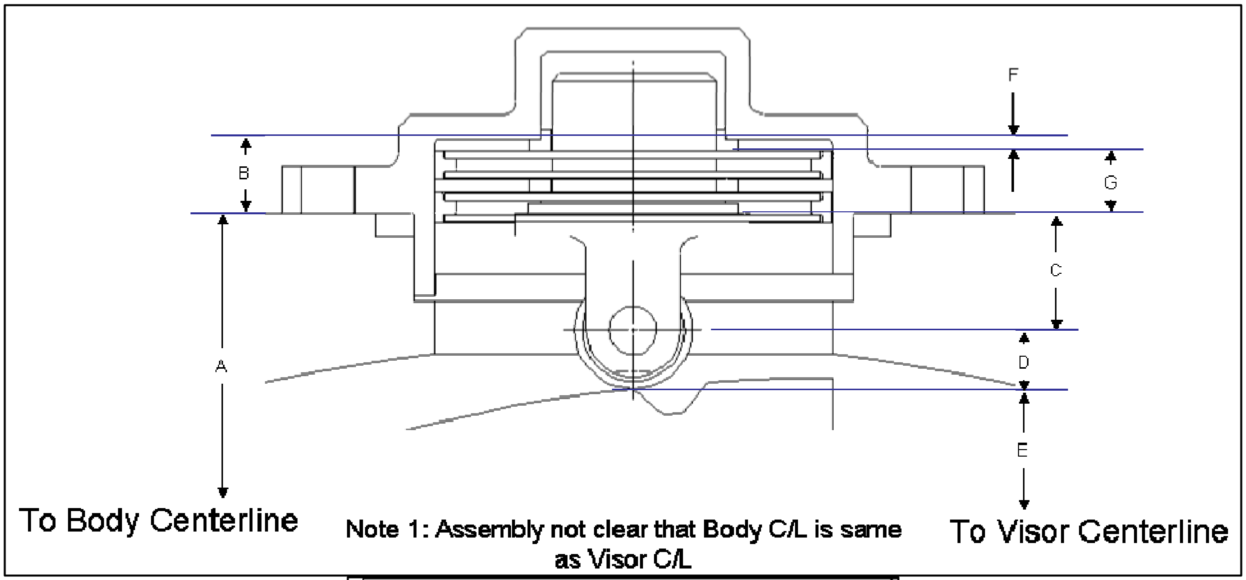


Figure 11: Crack can be seen through the compatibility testing mark and from the inner to outer diameters

During further examination of all available data it was noted that the visor to valve body height, recorded during the visor mold impression and grinding work, was out of family. This information kicked off a tolerance stack up analysis. The third cracked roller kicked-off an effort for a more in-depth investigation of alternate causes. Because the first two causes that were examined, the dimple and the sharp edge, did not preclude another cracked roller, it was necessary to look for a less obvious cause. Because the third failure was after only one flight, resources and attention not previously available were given to the problem.

The out-of-specification measurement of the visor height prompted the tolerance stack-up investigation. The measured distance of the visor from the valve body was used as a basis for a tolerance stack-up analysis. Actual measurements of the installed detent mechanism components were used, including a force-deflection curve of the Belleville spring stack set-up. The stack up of the individual components was subtracted from the visor height to determine if interference was possible. Interference would result in the spring stack reaching its solid height and imparting unexpected high loads on the roller. It was determined that combinations of nominal piece parts tolerances could result in deflections that caused the Belleville spring stack to go flat and introduce the high loads onto the roller. An illustration of the mechanism and the measurements used in the analysis are shown in Figure 12. As a solution, piece parts were carefully selected to produce an acceptable assembly on the low side of the tolerance band. This should preclude the spring stack from reaching a solid deflection height. Further mitigation was to machine an angle in the retainer surface that contacts the follower. The surface was angled to 2 degrees based on the marks left by the roller on the retainer. These marks indicated the angle at which the roller was moving when in contact with the visor. The modified retainer allows additional movement of the follower and prevents binding at the follower-retainer interface. This reduction in binding also reduces the load being applied to roller.



A	Valve center to housing
B	Cover height
C	Follower height from center pin to spring seat
D	Roller radius (pin/roller clearance stackup neglected)
E	Valve center to visor surface.
F	Inner spacer thickness
G	Spring stack height

Figure 12: Detent Mechanism Tolerance Stackup