Predict Service Life of Actuator Diaphragms?

NOW YOU CAN

BY PAUL GASSMAN & TED GRAUBAU

Throttling and powered on-off valves provide the control of fluids within a broad range of process industries and applications. In order to operate, these valves rely on a "motor," or actuator to position the valve's controlling element, such as a plug, ball, or disc.

Today's control valve actuators are typically pneumatically powered and available in a number of styles, including spring-and-diaphragm, piston, and rotary vane. Of these designs, most control applications utilize spring-and-diaphragm actuators for several key reasons.

A chief advantage of the spring-and-diaphragm actuator is that the actuator spring provides a simple, positive method of returning the valve to its fail-safe position upon loss of supply air. When compared to a piston actuator, a diaphragm actuator generally requires lower air pressure to create a given thrust, due to its larger effective area. The diaphragm design provides smoother and more efficient operation since there is no piston O-ring to create sliding friction.

Diaphragm Reliability

Despite these advantages, the possibility exists that the diaphragm might fail. Whether the failure is slow to develop or sudden, the end result is either poor or non-existent valve operation. Understanding why actuator diaphragms fail is the first step in gaining extended actuator and valve performance.

Actuator diaphragms can fail for a number of reasons. The most prevalent include:

- **Ultraviolet Light and/or Ozone Damage.** Nitrile rubber, the dominant material used for actuator diaphragms, is especially susceptible to damage from UV and ozone. This damage usually occurs during storage before the diaphragm is even put into service and occurs when the rubber is in a state of tensile stress—which may be as mild as being folded or hung from a pegboard.

Ultraviolet light that falls directly on the rubber surface affects a chemical reaction between the oxygen in air and the unsaturated (double) carbon=carbon bonds in the polymer chain. This causes a scission of the carbon "backbone" of the polymer, resulting in a crack. Continued exposure to UV light allows the crack to progress further into the material. Such cracks appear as crazing with an orientation that is normal (90°) to the tensile stress. ***(Figure 1)*** This is the kind of damage usually termed "weather checking" and visually matches that often found on the sidewall of tires.

Ozone (O_3) imparts the same sort of damage to elastomers. ***(Figure 2)*** In fact, some researchers believe that UV impingement on a rubber surface actually generates ozone locally from the atmosphere, and that the polymer damage is actually from the reaction with ozone.

Avoid this premature failure mode by appropriately packaging and storing the diaphragm. Utilize black plastic bags and boxes to prevent light exposure, reduce air exchanges, and avoid tensile stresses preceding installation into an actuator.

Diaphragm manufacturers can add anti-ozonants to rubber compounds susceptible to UV or ozone to improve diaphragm shelf life. Ozone and UV weather resistance can be tested by accelerated, relative tests such as ASTM D518 or D750, respectively.

• **Loss of Retention.** Retention loss occurs when the clamping force exerted by the bolting of the actuator casings causes the rubber to relax and take what is known as a "compression set." The rubber squeezed between the casing flanges tends to relax over time to a value that it then sustains. Additional tightening of the casing bolts will not change this value greatly since it is intrinsic to the material.

Excessive clamping typically creates a ledge of rubber just inside of the flange faces, a scalloped appearance of the diaphragm extruding outside the diaphragm case, and delamination of the rubber from the fabric. Distortion of the bolt holes also can occur with a resulting loss of seal integrity.

Other factors that affect performance in this regard are the thickness of the diaphragm, rubber/fabric volume ratio, and adhesion to the casing flange surfaces. Loss of retention results in stretched, teardrop shaped bolt holes ***(Figure 3)*** and eventual loss of the flange seal.

Formulation of the rubber can be optimized to minimize compression set *(e.g., through increased cross-link density, molecular weight, and carbon black volume ratio.)* The test methods for assessing this property are described in ASTM D395. This is a typical benchmark test for actuator diaphragms.

• **Environmental.** Incompatibility failures usually occur when the diaphragm is subjected to an unanticipated vapor or liquid that affects the integrity of the rubber coating and perhaps underlying fabric. Air-operated actuators generally receive compressed air from oil-lubricated compressors. Small amounts of oil vapor can be carried along with the compressed air, and if not otherwise condensed and filtered out, can end up in downstream equipment.

Most nitrile rubber diaphragms have good oil resistance. However, some oils with low aniline points can cause significant swelling of nitrile. There has been increased recently use of di-ester-based synthetic oils that have poor compatibility with nitrile and most other elastomers.

Figure 1: Oxidation cracking typical of exposure to high temperature or extremely long service at normal application temperatures. This is the predominant failure mode of a diaphragm at the extreme limit of polymer aging.

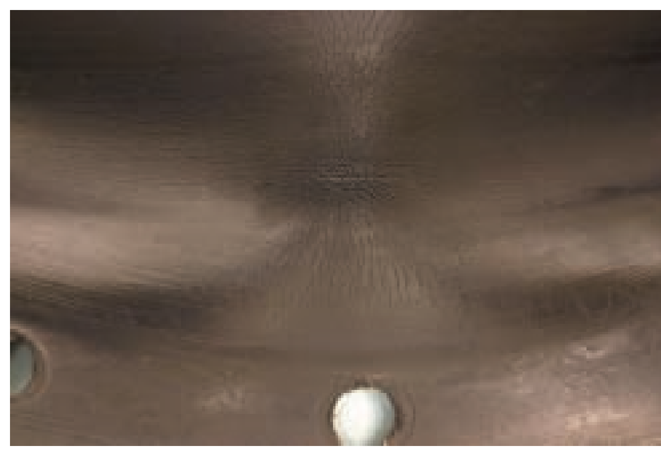

Figure 2: A Nitrile test specimen after 24-hour exposure to 300 ppb ozone. Notice how the crazing is generally normal to the direction of the applied tensile stress imposed by bending. Also, the crazing is so small that it is unnoticeable until the specimen is flexed to open the small cracks. Contrast the size and population of these cracks with the oxidation cracks depicted in Figure 1.

Environmental soak tests can be performed to determine the environmental resistance of diaphragm materials. ASTM D471 or D5964 tests are typical and measure such parameters as change in hardness, volume swell, change in mass and/or changes in tensile properties. This is also a standard benchmark test for actuator diaphragms.

• **Temperature.** Failures can occur when diaphragms are exposed to temperatures higher than allowed by their specifications. A typical example would involve the safety relief of excessive steam pressure. The relief valve is normally closed, so the lack of flow minimizes actuator and diaphragm exposure to high temperature. However, when the safety relief valve is called into service and opens, heat is radiated to the actuator as well as conducted up the valve stem and actuator rod to the diaphragm.

Oxidation is a chemical process that has a rate of reaction that is exponentially related to temperature. As such, a relatively short exposure of a diaphragm to high temperature can impart the same amount of damage that normally would take years to accumulate at ambient temperatures. If compression set resistance is marginal, over-temperature can cause a loss of flange retention. If compression set is robust, over-temperature ultimately will oxidize the rubber coatings on the diaphragm. The coatings will become brittle and then crack during stroking. These cracks typically are large compared to ozone/UV damage and allow loss of air pressure through the thickness of the diaphragm and/or to the fabric. The air pressure can wick to diaphragm perimeter and leak to the atmosphere.

• **Fatigue.** Fatigue failures in diaphragms take several different modes. A true fatigue failure can occur in rubber and other polymers similar to that experienced in metals. A crack initiates depending upon the number of stress cycles and stress amplitude, and propagates through the material to create a leak path. In severe cases, the reinforcing fabric may fatigue as well and cause a sudden, bursting failure.

A more common failure related to fatigue is actually an abrasion failure. With each pressure cycle the diaphragm tends to expand and contract, or "breathe." This breathing imparts motion of the diaphragm relative to its supporting diaphragm plate, which in turn abrades bits of material off the diaphragm. Eventually the abrasion removes enough material to weaken the fabric and cause a bursting failure. ***(Figure 4)***

OEM's concerned about reliability usually coat both sides of the diaphragm with rubber to protect the fabric from abrasion. While rubber coating is only required on the pressure side of the diaphragm to function, the rubber coating on the side facing the diaphragm plate vastly improves cycle life. ***(Figure 5)*** In fact, the cycle life of the diaphragm can exceed that of return springs as well as the diaphragm cases. This is a typical benchmark test for actuator diaphragms.

• **Delamination.** As the name infers, delamination is the breakdown of a composite diaphragm into its individual components, fabric and rubber. Several root causes can initiate this failure mode. Inadequate bond strength between the fabric and rubber is the most obvious. Some fabric-and-rubber combinations have intrinsically low chemical bonding imparted by the molding process. This can be improved by selecting a fabric with an open weave that has larger interstices that allow the rubber to "strike through" and bond to itself on the other side.

Also, primers can be applied to the fabric to improve the chemical bond. These primers are typically a solvent-diluted solution of the uncured rubber compound. Because of its low viscosity the primer is capable of permeating farther into the

Figure 3: Typical teardrop shaped bolt holes due to loss of retention (compression set of the diaphragm) and stretching. Notice also the scallop shapes outside each bolt hole and the ledges of displaced rubber both inside and outside the flange.

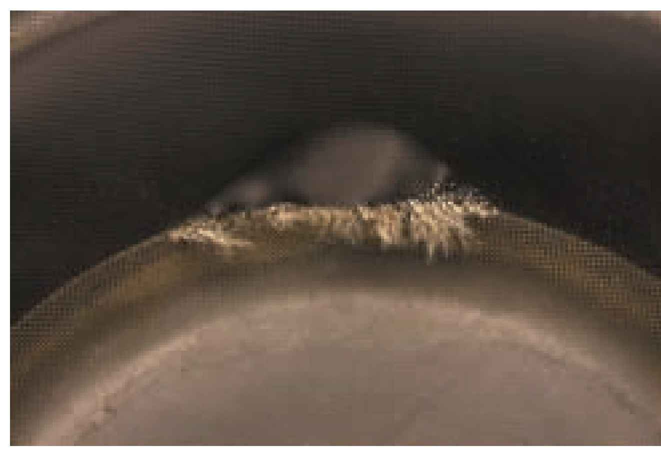

Figure 4: A one-side-coated diaphragm after cycle testing. Notice that the edge of the diaphragm plate has worn and frayed the fabric until a bursting occurred. This happened after just a few hundred thousand cycles.

individual yarns.

Swelling of the rubber due to external exposure can cause the rubber to expand and to then shear away from fabric that has not expanded in the same manner. This can happen when compressor oils or other contaminants wet the diaphragm.

Delamination can also result from over-clamping, as discussed earlier. Despite its root cause, delamination generally disrupts a diaphragm's ability to perform as a single composite material, and forces the rubber coating and fabric to perform individually without the other's benefit. This usually results in loss of pressure-retaining integrity through the thickness of the diaphragm.

• **System Design.** Bursting is a sudden, structural failure of the diaphragm resulting from either inadequate diaphragm strength or an unanticipated overpressure event. For example, failing to install an upstream pressure regulator has caused more than one diaphragm failure in complex systems.

Punctures rarely happen, but have been observed when actuators have been dissembled for maintenance. Nuts or bolts that were left inside the diaphragm case following maintenance sometimes show up later after they damage the diaphragm and cause an unscheduled maintenance event.

Addressing the Problems

• **Rubber Development.** Control valve use within the nuclear power industry prompted the search for a diaphragm with a service life that not only was longer than typically experienced, but also one that was predictable. Added to these criteria were resistance to high-energy radiation and a fabric that could withstand exceptionally high temperatures. While these requirements were perhaps out-of-the-ordinary for valve use within other processing industries, it became clear that the results of meeting the nuclear industry's needs could be applied by all.

Development efforts started with a search for a material with improved oxidation resistance at elevated temperature. A variety of elastomers offer improvements over the standard nitrile, and ultimately, ethylene propylene diene (EPDM) was chosen because of its breadth of advantages.

EDPM boasts improved temperature resistance, UV/ozone resistance, excellent compression set, abrasion resistance, low temperature flexibility, tensile strength and high-energy radiation resistance. The ethylene propylene diene terpolymer is essentially a saturated carbon chain without double carbon=carbon bonds, except the small amount of diene polymer purposely added to create crosslinking sites for the cure system. In its cured state, the lack of double carbon=carbon bonds leaves this polymer less reactive to all forms of oxygen, which improves its heat resistance.

An exception to EDPM's superior attributes is oil resistance. EPDM is chemically similar to hydrocarbon oil, so it characteristically has a high solubility constant for oil and exhibits the associated volume swell. Confident that most valve users keep air systems relatively oil free, especially those operating at elevated temperatures, the low resistance to oils was considered an acceptable trade-off in light of the significant improvements in other, more critical properties.

Figure 5: A diaphragm coated with rubber on both sides of the fabric and cycle tested similarly to Figure 4. Even after one million full pressure cycles, only some rubber crumb is visible from abrading the edge of the diaphragm plate, and the fabric is still protected.

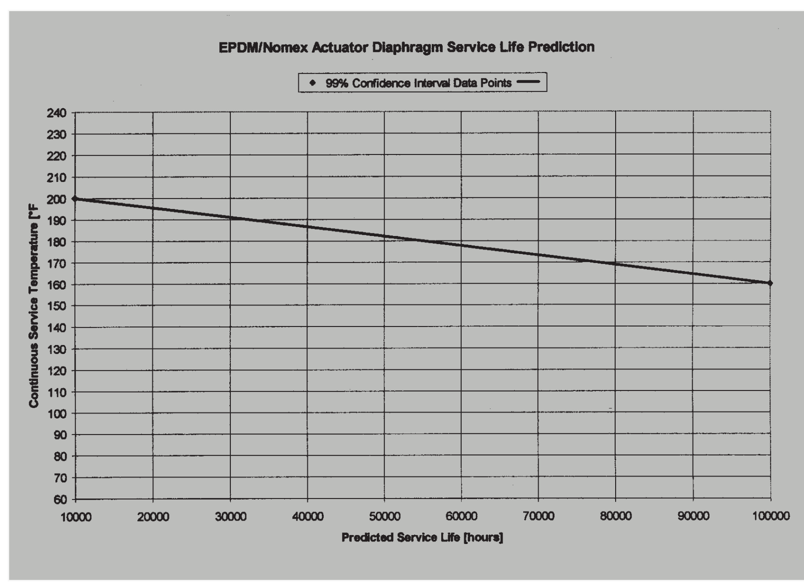

Figure 6. Linear graph that enables the predicting of EDPM/Nomex diaphragm service life. The data presented is based on extensive testing over a four-year period by a major control valve manufacturer.

Finding a Fabric

Having developed a rubber compound with the desired properties, it was time to select the fabric. One of the nuclear industry criteria was that the fabric would survive a significant over-temperature excursion. It would be acceptable for the rubber coating to crack and leak, but the fabric had to stay intact to allow operation provided a sufficient air supply was applied.

Natural fibers such as cotton and silk have good temperature resistance, but their availability is unreliable due to the supply demands of the garment industry. Synthetic fibers such as nylon, polyester, polytetrafluorethylene (PTFE) and aramid (Nomex®) have become the mainstays of industrial products such as diaphragms.

Nylon and polyester have excellent properties for reinforcing diaphragms, but have more limited temperature resistance than the aramids. PTFE has good temperature resistance, but offers lower strength across the temperature range than any of the other synthetic fibers. Kevlar® aramid has excellent high temperature properties, but low elongation before breaking.

Although it has lower strength than Kevlar®, Nomex® exhibits excellent high temperature properties and excellent elongation. Good elongation before breaking is important in order to more nearly match the EDPM's properties and to provide a diaphragm that absorbs pressure impulses and other impacts. Nomex® can tolerate significant temperature excursions far better than the EPDM coatings. Therefore, the diaphragm's structural integrity would be intact long after the rubber coatings have become brittle, cracked and started to leak, thereby allowing a more graceful, "leak-before-break" failure mode.

The Prediction Curve

Having chosen the fabric and the elastomer, it was time to test the two materials as a molded composite. Initial tests included Mullen burst testing to confirm composite strength as well as conducting a million-cycle fatigue test. The more telling tests would be the accelerated aging tests.

It was decided to create a time-to-end-of-life test at various temperatures by assembling diaphragms into complete

Studies have shown that the aging mechanism in elastomers is basically a chemical oxidation process that is governed by the same laws as other types of chemical reactions. The aging mechanism in elastomers is characterized by changes in the molecular structure which occur naturally under the influence of oxygen, heat, light, radiation etc. The polymer chain and cross link bonds between polymer chains are selectively broken and replaced by oxygen bonds which interrupt the continuity of the material and degrade its physical properties. This degradation process is time and temperature related and occurs at a rate unique to each polymer.

Arrhenius[1] was able to describe this time versus temperature relationship with the following equation:

$$dq / dt = A \times e^{-\Phi/KT} \quad (1)$$

where:

q = quantity of material reacted

dq / dt = reaction rate

T = absolute reaction temperature (°K)

Φ = Activation energy for the specific material (eV)

K = Boltzman's constant (8.617 10-5 eV/°K)

A = proportionality constant called the frequency factor

Since the reaction rate, dq/dt is inversely proportional to the time to failure of the material, 1/t can be substituted as the time to degrade a volume of material (in this case a diaphragm) to a specific extent (failure leakage). By substituting 1/t for dq/dt and taking the natural logarithm of both sides of this equation, it can be rewritten as:

$$\mathrm{Ln}(1/t) = \mathrm{Ln}(A) - \phi/KT \quad (2)$$

This expression can be rearranged as follows:

$$-\mathrm{Ln}(1/t) = -\mathrm{Ln}(A) + \phi/KT \quad (3)$$

$$\mathrm{Ln}(t) = -\mathrm{Ln}(A) + \phi/KT \quad (4)$$

$$\mathrm{Ln}(t) + \mathrm{Ln}(A) = \phi/KT \quad (5)$$

$$(\mathrm{Ln}(t) + \mathrm{Ln}(A))K/\phi = 1/T \quad (6)$$

$$\mathrm{Ln}(A)K/\phi + \mathrm{Ln}(t)K/\phi = 1/T \quad (7)$$

let $\mathrm{Ln}(A)K/\phi = a$, then

$$1/T = a + K/\phi \mathrm{Ln}(t) \quad (8)$$

Since K and ϕ are both constants, this equation fits the classic linear equation form, $y = m^x x + b$.

This relationship served as the basis for the service life regression and derivation of the activation energy value for the EPDM/Nomex® diaphragms tested during this project.

Note 1: Arrhenius, Svante August, 1859-1927, Swedish Chemist. A professor of physics in Stockholm in 1895; became director of the Nobel Institute for Physical Chemistry, Stockholm, in 1905. He received the 1903 Nobel Prize in Chemistry for originating the theory of electrolytic dissociation, or ionization (1884, 1887).

actuators and than soaking those actuators at elevated temperatures in kilns. The elevated temperature tests were conducted with the actuator diaphragm casings pressurized to the maximum allowable operating pressure. This final, functional test regimen not only confirmed the ultimate failure mode (thermal oxidation), but with enough iterations, also allowed developing a time-to-failure vs. temperature curve to use in predicting diaphragm service life.

Following high temperature testing of dozens of EPDM/Nomex® diaphragms over a four-year period, enough data was accumulated to extrapolate the findings to lower, more typical application temperatures. (Test temperatures varied from 375° to 275°F with test durations exceeding 2000 hours at 275°F.) Statistical analyses were performed on the test data to determine a one-sided, 99% confidence interval so that conservative life predictions could be identified. The result of that data analysis is represented in a simple, linear graph ***(Figure 6)***. If the service temperature for the actuator is known, the service life can be conservatively chosen from the graph.

The data is based upon steady-state conditions. If application temperatures are variable, the maximum temperature should be used for a conservative estimate.

Also, the data was derived using high-quality compressed air. Lesser air quality standards may negatively affect diaphragm life, especially if O_3, NO_x and SO_x levels are elevated.

Diaphragms are critical, dynamic sealing components that often dictate control valve maintenance intervals. Experience shows that they can be relatively fragile. However, with sufficient technology development and information sharing between valve users, diaphragm service can be both extended and predictable, so that process up-time is optimized. Regardless of diaphragm material, users must still follow certain basic maintenance and operation precautions as presented by premium valve OEMs. VM

Paul Gassman is Marketing Manager at Fisher Controls International, Inc., Marshalltown, IA; 641.754.0311; www.frco.com; Ted Graubau is Manager, Advanced Technology, with Fisher Controls International, Inc.

Emerson Process Management
Fisher Controls International, Inc.
205 South Center Street
Marshalltown, Iowa 50158
T 1 (641) 754-3011
F 1 (641) 754-2830
www.Fisher.com

FISHER®

EMERSON™
Process Management

D350932X012 Printed in U.S.A.