AS SEEN IN
VALVE MAGAZINE
FALL 2002 VOLUME 14, NO. 4

Superior Actuator Diaphragm Material for Control Valves in Low Temperature Applications

A newly developed actuator diaphragm material for use in control valve applications provides extended service temperature capability, particularly at sub-zero temperatures.

by Ted Grabau

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.

This article presents the development of a superior diaphragm for low temperature applications.

Diaphragm Performance

One of the concerns addressed in developing a diaphragm for control valves is its intended service temperature [1]. The diaphragm is normally a composite construction of a fabric to provide membrane strength and a thermosetting elastomer (rubber) material to provide a pressure-tight barrier.

At the high end of the temperature spectrum, elastomers tend to lose their strength and other mechanical properties. However, at the low end of the temperature spectrum, they tend to stiffen and ultimately become brittle. All elastomers undergo a glass transition temperature, usually abbreviated T_g. Well below T_g, at what is called the brittle temperature, an elastomer is totally brittle and will shatter like glass when flexed. Fortunately, this transition does not occur abruptly. As the temperature is approached from elevated temperature, a marked increase of the stiffness as measured by the tensile, flex or compression modulus is noticeable. Thus, control valve performance can be negatively impacted by operating at temperatures close to the T_g of the actuator diaphragm due to the additional stiffness subtracting from the total thrust available from the actuator.

The value of T_g is dependent upon the polymer type, its molecular weight, crosslink density (for thermosetting materials) as well as formulated fillers and especially plasticizers. ***Table 1*** lists different thermosetting elastomers and their respective brittle temperatures, T_g and stiffening ranges.

The Challenge

Oil and gas exploration continues in the most remote places on the globe, including extreme northern climates in Alaska, Canada and Siberia. Recent control valve customer specifications for these locations have included operability at -55°C (-67°F).

In order to comply with this specification, some standard and optional diaphragm materials were tested. The industry standard diaphragm elastomer material for valve actuators is nitrile (NBR), which is an acrylonitrile (ACN) butadiene (BR) copolymer. The NBR formulation tested for this application has been specially formulated for low temperature flexibility by increasing the volume fraction of butadiene and adding a plasticizer. While the original qualification testing of this material includes surviving a cold bend test (ASTM D2136) at -51°C (-60°F), it becomes noticeably stiffer at that temperature. The last temperature at which a sample survives a cold bend test correlates very well with its brittle temperature. The hardness increased from 72 Durometer on the A scale at room temperature to 72 Durometer D at -51°C (-60°F).

A diaphragm material with improved low temperature flexibility is an optional material that is usually sold into elevated temperature applications. That material is methyl

Elastomer Material	Glass Transition Temperature, T_g	Stiffening Temperature Range	Brittle Temperature
Nitrile, 38% ACN	-25°C (-13°F)	-1 to -29°C (+30 to -20°F)	-40°C (-40°F)
Nitrile, 30% ACN	-32°C (-25°F)	-18 to 10°C (0 to -50°F)	-57°C (-70°F)
EPDM	-65°C (-85°F)	-29 to -46°C (-20 to -50°F)	-62°C (-80°F)
VMQ	-107°C (-160°F)	-40 to -80°C (-40 to -112°F)	-90°C (-130°F)
PVMQ	-127°C (-196°F)	-50 to -120°C (-58 to -184°F)	-118°C (-180°F)
FKM	-20°C (-4°F)	-7 to -120°C (+20 to -33°F)	-25°C (-13°F)

Table 1. Glass transition, stiffening range and brittle temperatures of selected thermosetting elastomers.

vinyl silicone (VMQ). It passed the cold bend test at -62°C (-80°F), during material qualification testing and maintained reasonable flexibility at that temperature. The VMQ silicone material hardness increased from 59 Durometer on the A scale at room temperature to only 65 Durometer A at -51°C (-60°F).

After consulting with silicone polymer chemists about the intended service for these diaphragms, a phenyl methyl vinyl silicone (PVMQ) was recommended for inclusion in the test program as it reportedly has an even lower T_g than VMQ.

Testing

A dynamic mechanical analysis (DMA) was performed on each of the three materials to look for differences in stiffening temperature ranges. DMA testing was begun at -80°C, the lower limit of its refrigeration unit. A 10mm sample of the material was dynamically compressed at 1 Hz. while the temperature was increased 2°C per minute to 60°C. DMA testing revealed considerably different stiffness versus temperature curves for the elastomers across the whole temperature range, especially below -20°C (-4°F). ***See Figure 1 on page 28***. This stiffness value is expressed by the compressive storage modulus in a DMA test.

As can be seen in Figure 1, the NBR material starts at a very stiff plateau and starts to drop dramatically at about -45°C. This is described as the brittle onset temperature as measured by DMA storage modulus. The storage modulus continues to drop dramatically to around -20°C (-4°F), where it flattens out at a much more constant level but is still the stiffest material tested. So, while the nitrile material is usable down to about -45°C, it becomes very stiff and would hamper control valve performance.

The VMQ material has a considerably lower modulus than the NBR material at -80°C (-112°F) and would appear to be very near the onset of its brittle temperature. Its storage modulus drops to through the range to about -40°C where it flattens abruptly and remains the lowest modulus material of any of the diaphragm elastomers.

The PVMQ material has a considerably lower modulus than either of the other materials at -80°C (-112°F). As the slope of the modulus curve is still positive, it would appear that -80°C (-112°F) is not even close to its brittle temperature. In addition, the change in modulus through the entire temperature range is very minimal and would thus offer the most consistent performance through dramatic temperature changes.

Definitions per the Plastics Design Library Glossary of Terms:

- **Brittle Temperature**—Temperature at which a material transforms from being ductile to being brittle, i.e., the critical normal stress for fracture is reached before the critical shear stress for plastic deformation.
- **Dynamic Mechanical Analysis**—A technique that employs a low-strain, oscillatory stress in order to quantify the viscoelastic behavior of materials. Commonly referred to as DMA.
- **Brittle Temperature**—Temperature at which a material transforms from being ductile to being brittle, i.e., the critical normal stress for fracture is reached before the critical shear stress for plastic deformation.
- **Glass Transition Temperature**—The temperature at which an amorphous polymer changes from a hard and relatively brittle condition to a viscous or rubbery condition.
- **Modulus**—The ratio of stress to corresponding strain below the elastic limit of the material.
- **Plasticizer**—A substance incorporated into a material such as plastic or rubber to increase its softness, processability, and flexibility via solvent or lubricating action or by lowering its molecular weight. Plasticizers can lower melt viscosity, improve flow, and increase low-temperature resilience of material. Most plasticizers are nonvolatile organic liquids or low-melting-point solids, such as dioctyl phthalate or stearic acid. They have to be non-bleeding, nontoxic and compatible with material. Sometimes plasticizers play a dual role as stabilizers or crosslinkers.
- **Storage Modulus**—In a dynamic experiment, that portion of the stress-strain response which is in phase with the applied stress. The storage modulus is related to that portion of the polymer structure that fully recovers when an applied stress is removed.
- **Thermosetting Elastomer**—A large class of polymers that can be stretched at room temperature to at least twice their original length and, after having been stretched and the stress removed, return with force to approximately their original length in a short time. To attain this elastic property the rubbers must be crosslinked or vulcanized, usually by heating in the presence of various crosslinking agents and catalysts. There are natural and synthetic rubbers, dienic rubbers (nitrile, butadiene, chloroprene), silicone rubbers, and urethane rubbers. Used often as impact modifiers/fillers in plastics.

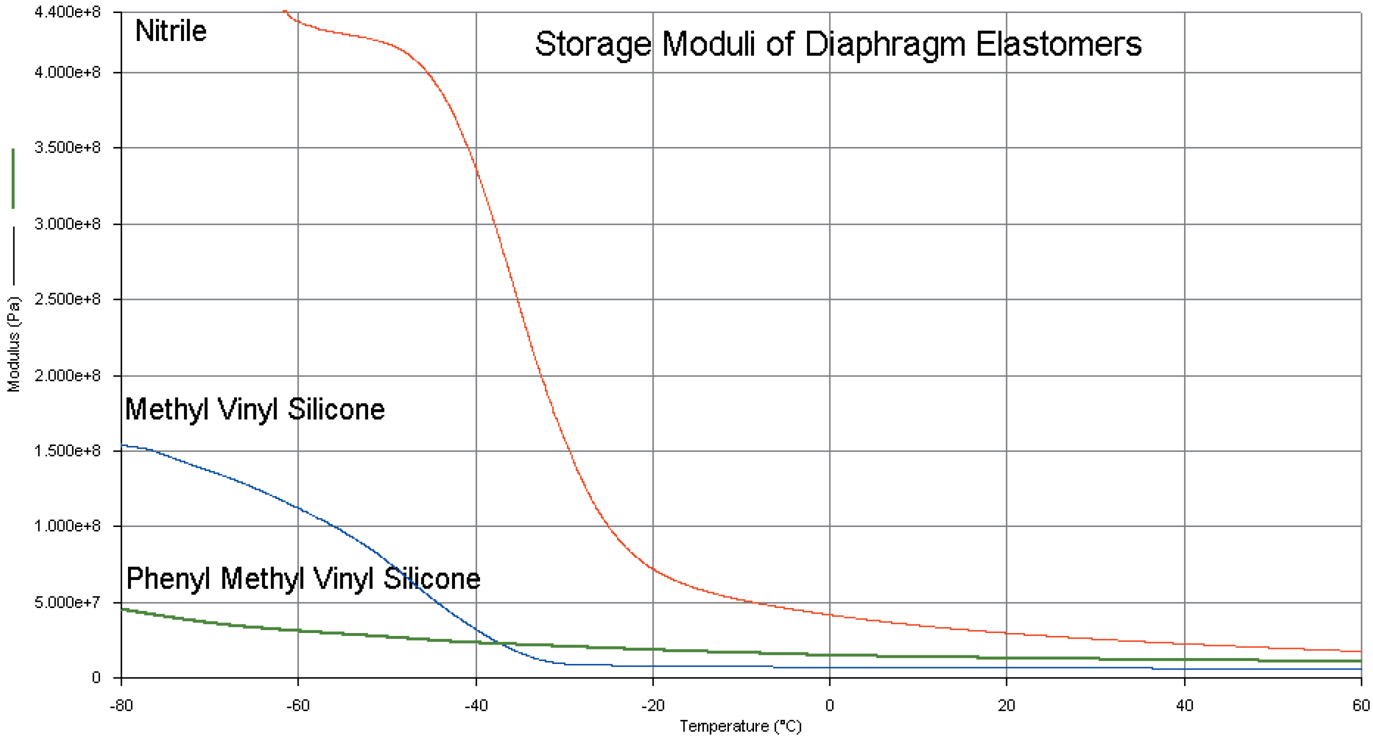

Figure 1. DMA performed on 10mm diameter samples of nitrile (NBR), methyl vinyl silicone (VMQ) and phenyl methyl vinyl silicone (PMVQ) rubber in compression mode.

Control Signal Range, mA	Δ Actuator Pressure Range, bar [psig]	Methyl Vinyl Silicone Diaphragm Stroke, mm [inches]	Phenyl Methyl Vinyl Silicone Diaphragm Stroke mm, [inches]
4-20	0.28-1.10	6.274	13.335
	[4-16]	[0.247]	[0.525]

Table 2. Comparative actuator strokes.

Since the stiffness of the two silicone-based diaphragms was dramatically less than the standard nitrile, only they were chosen for testing in a full-scale actuator placed in an environmental chamber capable of achieving -55°C (-67°F). A spring and diaphragm actuator was connected to a valve bonnet with polytetrafluoroethylene packing adjusted for minimal friction. The actuator was connected to a current to pressure (I/P) transducer and placed in an environmental chamber. The 4-20 mA signal to the I/P transducer was set to output 4-16 psig into the actuator. During setup, the control signal was set at 12 mA in order to achieve a mid-stroke position on the actuator and the temperature reduced to -55°C (-67°F). After temperature equilibration for 8 hours, the control signal was swept from 12 mA to 4 mA and finally to 20mA. Actuator pressure and stem position were recorded. The results are tabulated in ***Table 2***.

Conclusion

As can be seen from the table, the same change in control signal and resultant actuator pressure resulted in twice the actuator stroke for the PVMQ diaphragm than for the VMQ diaphragm. This was solely because of the lower stiffness (modulus) of the PVMQ at the test temperature as a result of its suppressed brittle temperature. The PVMQ silicone diaphragm offers far superior flexibility at low temperatures which will translate to better, more consistent actuator travel and therefore better process control. VM

The author is Manager, Advanced Technology, Emerson Process Management, Fisher Controls Intl., Marshalltown, IA; 641.754.3011; www.fisher.com; ted.grabau@emersonprocess.com.

FISHER®

EMERSON™ Process Management