DIAPHRAGM DEVELOPMENT TRENDS FOR SAFE LEAKFREE RECIPROCATING PROCESS PUMPS

by

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ABSTRACT

The application of diaphragm pumps for metering and conveying of fluids are continuously expanding because they provide zero-leakage, can run dry, have superior efficiency, offer high reliability, maximize safety and minimize maintenance. However, end users should develop an understanding of the functional details involved and the necessity of a systems approach when installing and operating these pumps. The diaphragm design and the various influences on endurance and reliability are evaluated. Among others: material selection, the diaphragm motive system, the pump head/diaphragm, and installation/diaphragm interactions, diaphragm clamping, sandwich diaphragm design, computation of stresses and fatigue for both metal and PTFE diaphragm. Objectives for further optimization of diaphragm designs and comments about economy, performance and reliability close the discussion.

INTRODUCTION

Concerns for protection of the environment are increasing. Legal requirements cove-ring this field are getting more stringent. These conditions pose heavy demands on the manufacturers and users of industrial machinery. In most cases, only hermetically sealed process equipment will be able to meet the resulting restrictions. In this context, leakproof machines (i.e., pumps and compressors) are key components. Diaphragm pumps offer the optimal solution for handling toxic, dangerous, noxious, sensitive, abrasive or corrosive fluids, if favorable hydraulic conditions (high head, low volume) for reciprocating, positive displacement pumps exist.

The diaphragm constitutes the central element in these pumps, simultaneously serving a dual function as a static seal, and a flexible isolation of the working volume by acting as the displacement element. In its role as a static seal, the diaphragm replaces the piston seal of conventional piston type pumps. With the diahragm in direct contact with the fluid, it consequently assures hermetic, leakproof operation. Details of diaphragm pumps are described in the current literature [2, 3, 4, 5, 6].

A review is offered in Figure 1 of the operational ranges of mechanically and hydraulicallly actuated diaphragms, of diaphragm materials, and current power ratings of diaphragm pumps.

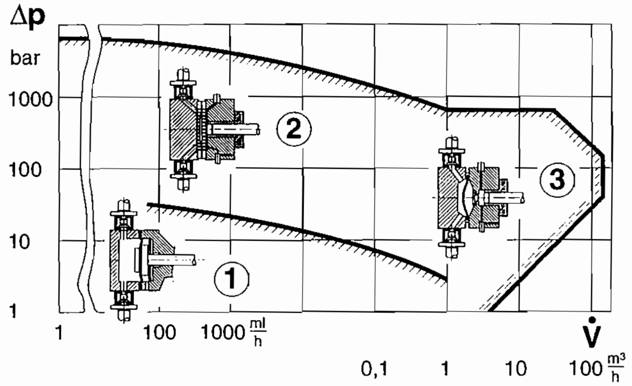


Figure 1. Application Range of Process Diaphragm Pumps: 1) mechanically driven diaphragm; 2) metal diaphragm, hydraulically driven; and, 3) PTFE diaphragm, hydraulically driven.

Characteristic features of diaphragm process pumps for metering or conveying applications are:

- Service life of the diaphragms reliably exceeding 10,000 hr.
- Diaphragms made of polytetrafluorethylene (PTFE) for pressures up to 5000 psig (350 bar) and temperatures up to 300°F (150°C). For higher pressures/temperatures, the diaphragms are made of austenitic steel (or similar materials). This material selection reliably meets the high demands for chemical and thermal durability. The use of elastomeric diaphragms coated with a layer of PTFE is limited.
- The design of the diaphragm clamping area assures a hermetic seal. Diaphragm condition can be monitored while hermetic pump conditions are maintained (sandwich type diaphragm).
- Compatibility with the process plant.
- Compatibility with the automation system of the plant.
- Excellent volumetric and energetic efficiency.
- Safely capable of running dry.
- Capability of selfpriming and automatic selfventing.

The present state-of-the-art and foreseeable trends are reported on for further development of this type of pump, with special attention towards the design of the diaphragm.

THE DIAPHRAGM WITHIN THE ENTIRE SYSTEM

The diaphragm transmits the reciprocating motion of the drive of the pump to the fluid. This inherent mode of operation not only results in a pulsating delivery of fluid, but also in an interaction with the masses of fluid within the pipe system (Figure 2). The diaphragm design has to pay attention to the various loads specific to the way the diaphragm is incorporated into the design of the pumping system.

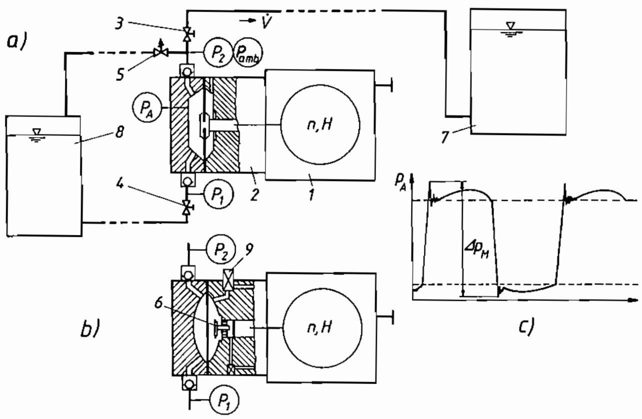
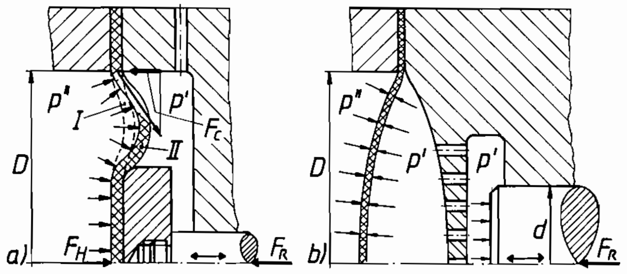


Figure 2. Diaphragm (Pump) within the System: a) mechanically driven diaphragm, b) hydraulically driven diaphragm, and c) tempory working space pressure.



$p'' >> p' = p_{amb}$

$F_H = F_R + F_C = \frac{\pi D^2}{4} (p'' - p')$

$p'' \approx p'$

$F_R = \frac{\pi d^2}{4} p'$

Figure 3. Diaphragm Drive System and Strain: a) mechanically driven diaphragm, b) hydraulically driven diaphragm, and 1 loaded, II nonloaded diaphragm.

Mechanically Driven Diaphragm (Figure 3 (a))

In addition to the loads resulting from diaphragm deflection while acting as the displacing element, in this configuration, the diaphragm has to support the loads caused by the pressure difference between the fluid side and the drive side of the diaphragm. The load to be supported increases not only proportional to the pressure difference, but also with the square of the diameter of the diaphragm (Figure 2 (a), bottom). For this reason, mechanical actuation of the diaphragm is limited to moderate pressure differences (< 300 psig/20 bar) and power ratings (hydraulic load < 0.75 hp/0.5 kW).

In this application, the diaphragm is not only subject to the effective pressure differences (Figure 2 (a), Δp_M), but also to all shocks and pulsations transmitted by the fluid [7, 8, 9]. In the case where valves 3 and 4 are closed by mistake during operation of the plant, or clogging of the pipe system, or clogging at the valves of the pump, the diaphragm will be stressed additionally, up to the pressure setting of the safety valve 5, by the vapor pressure of the fluid or by pressure shocks due to cavitation.

In applications employing mechanically driven diaphragms, undesirable stressing of the diaphragm must be carefully avoided by the corresponding layout of the entire system. Since the diaphragm is directly linked with the drive mechanism, it will always travel back and forth as designed.

To achieve a dependable return of the diaphragm, a spring of sufficient force must be employed [10].

In practice, mechanically driven diaphragms are mainly used in metering pumps with mechanical or hydraulic lost motion control. In these applications, attention has to be paid to the periodic pressure spikes occurring during reduced stroke length settings, and sufficient damping of these pulses must be provided when necessary.

In general, the operation of diaphragm pumps with mechanically driven diaphragm within a pipe system is not very demanding however, provided pressure shocks due to cavitation or other reasons are safely prevented.

In practically all designs equipped with mechanically driven diaphragms, the diaphragm always stays within a defined distance from the walls of the working space. Dirt particles or solids in the fluids will, therefore, usually not harm the diaphragm.

Hydraulically Actuated Diaphragm (Figure 3 (b))

In this design, virtually no unbalanced external forces are acted on the very flexible diaphragm. The only stresses the diaphragm experiences are due to deflection. The pressure difference is negligibly low and this design therefore adaptable to almost unlimited delivery pressures. Further, the size of the diaphragm has no effect on the stress. These favorable conditions for the diaphragm operation are the reason for the widespread and successful application of this design, since only by these features can a long service life be reliably assured.

In addition to the negligible stress to which the diaphragm is subjected, hydraulic actuation simultaneously permits precise transmission of the displacing action of the piston on the hydraulic fluid, by the diaphragm, on the process fluid. The characteristics of these pumps are virtually pressure-independent, assuring good volumetric and excellent energetic efficiency.

An overflow valve in the hydraulic system (Figure 2 (b), item 9) provides simple implementation of an important safety feature. In many cases, this device makes a separate safety valve in the fluid system unnecessary.

Hydraulic actuation of the diaphragm also involves various design details that influence the interaction with the system in which the pumps are installed.

Hydraulic Loss Replenishment

During the operation of the pump, an infinitesimal, but nevertheless continuous loss occurs in the hydraulic system. The hydraulic piston travels back and forth in its cylinder with a minute clearance through which a small amount of hydraulic fluid escapes. Secondly, automatic air bleed venting in the hydraulic system results in a second small loss. The hydraulic system is kept full by means of the diaphragm position control (DPC) [3]. Volumetric replenishment of the hydraulic fluid returned to the reservoir is performed at the rear dead center position of the diaphragm travel (Figure 4, item 2) by operation of a sliding gate valve (item 1). In Figure 5, the configurations of various approaches to solve this problem are illustrated and evaluated.

Snifting, or replenishment of hydraulic fluid, has to be disabled until the diaphragm reaches the rear dead center of the stroke, otherwise undesirable replenishment could overfill the hydraulic system, overextend the diaphragm and force it against the front wall of the pump head during the forward stroke. In the design of Figure 5 (2), for example, the conical locking pin (item 2) enables the snifting valve (item 4) with pin (item 3) only when the diaphragm (item 2) pushes the actuating disk (with axial holes) back towards the rear wall, which ultimately forms a mechanical stop. The design of Figure 5 (5), with external replenishment control is only used for very large diaphragm pumps in slurry services.

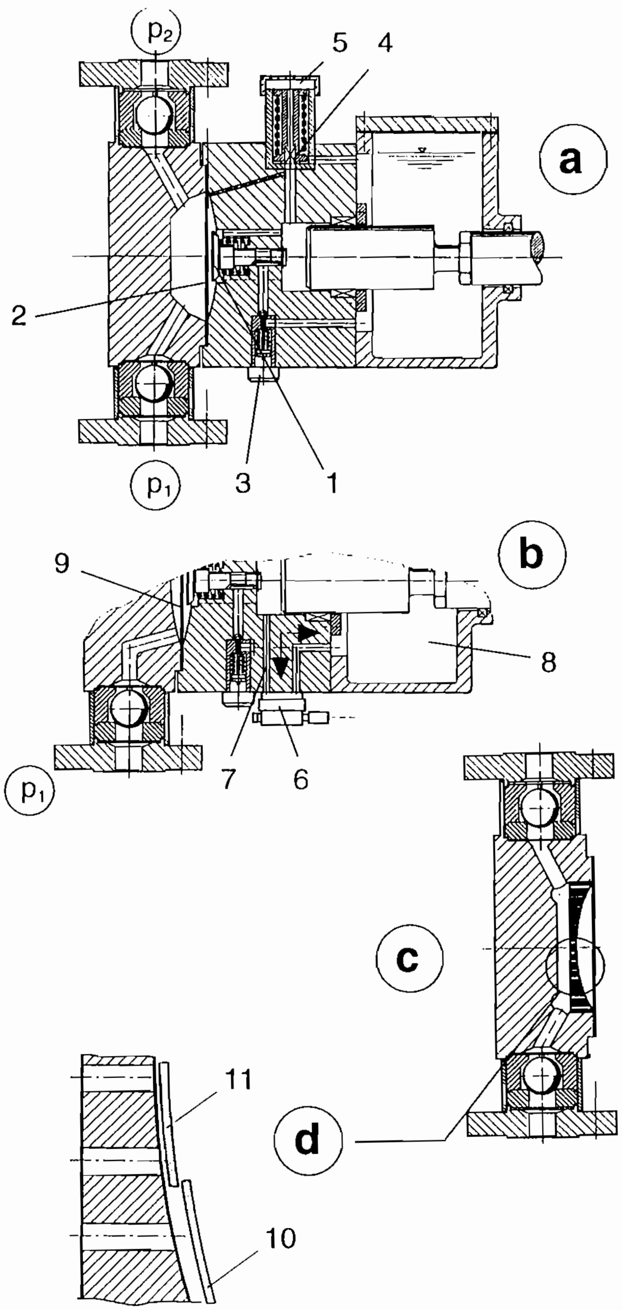


Figure 4. Diaphragm Position Control (DPC): a) principle function DPC; b) details and starting up relieve system; c) additional hole plate; and d) diaphragm position. 1) sliding gate valve; 2) snifting valve; 4) venting valve; 5) relief valve; 6) control valve; 7) connection bore; 8) hydraulic reservoir; 9) rear diaphragm position; 10) normal front diaphragm position; and 11) diaphragm support position.

Working Chamber Walls/Diaphragm Interaction

Diaphragm position control (DPC) is essential to the proper functioning of the pump. The diaphragm must be kept a safe distance from the front face of the working chamber during

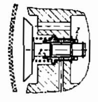
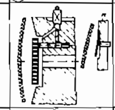
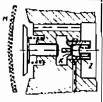
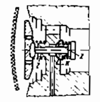
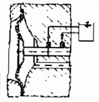
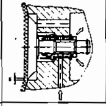
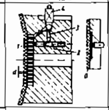
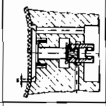
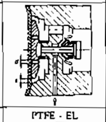
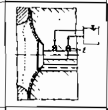
	Control valve with support disk ①	Mechanical limiting via control pin ②	Separate support disk with central pin and sliding control valve ③	Closing force compensation ④	Inductive diapragm position and control function pickup ⑤
Leakage replacement closed					
Leakage replacement open					
Diaphragm-material	PTFE	PTFE, metal	PTFE	PTFE - EL	EL
Sealing towards the leakage replenishing valve	Cylindrical gap (Z)	Mechanically limited replenishing valve (3)	Cylindrical gap (Z) and contacting seal (K)	Cylindrical gap (Z) and contacting seal (K)	Electromechanical valve
Sensing of the diaphragm position	Movable support disk	Spring loaded sensing disk	Spring loaded sensing disk	Spring loaded sensing disk	Sensing pin jointed to the diaphragm
Support of the diaphragm in the rear limit position	Smooth membrane support area with small gaps (S) for high operational pressure	Support disk with axial holes, operational pressure limited by the diameter d	Smooth membrane support area only with small gaps (S) for high operational pressure	Support area with axial holes (d) and a circular gap (S). Both limiting the operat. pressure	Smooth support area without any gaps or clearances

Figure 5. Morphology of Various DPC Systems.

normal operation (Figure 6 (a)) to avoid perforation of the diaphragm by any particles suspended in the fluid (Figure 6 (d)) or damage to the diaphragm by excessive local stress at discontinuities (e.g., holes) in the surface the diaphragm is forced against (Figure 6 (b)).

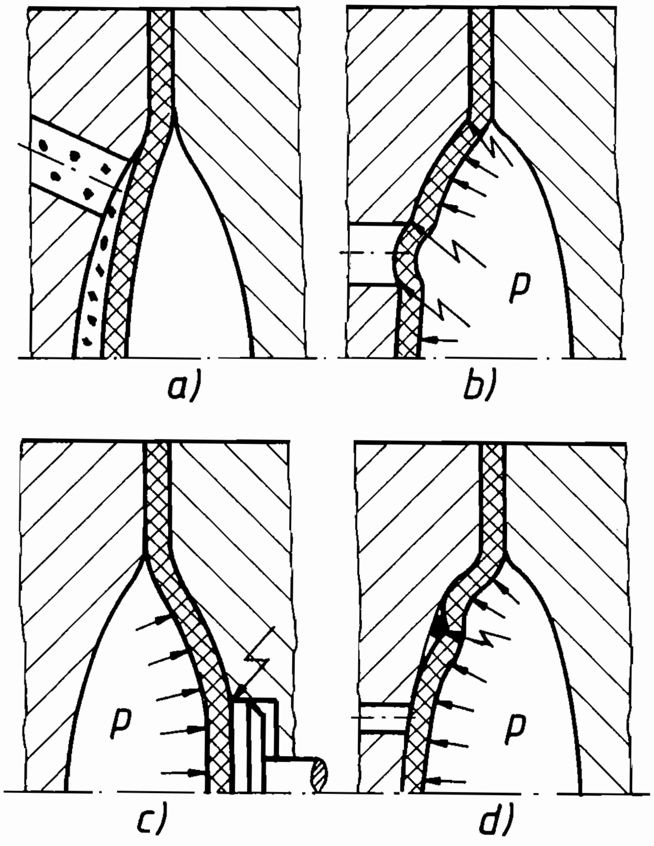


Figure 6. Diaphragm and Working Chamber Walls: a) diaphragm in safe distance from working space walls; b) damages by supporting compression (edges); c) damages by supporting compression (elevated suction pressure); and d) damages by particles.

To safely support the diaphragm in the presence of significant suction side pressure (Figure 6 (c)) requires a rear surface of the working chamber virtually without gaps or opportunities for stress accumulation. The design of these areas depends on the shape and the material of the diaphragm.

Basically, any compressive contact of the diaphragm with the surfaces of the working chamber will cause adhesive forces, implementing harmful asymmetrical local deformations of the diaphragm. To avoid such forces, particularly for metal diaphragms which are very sensitive to these disturbances, the surfaces of the working chamber are sometimes profiled by tangential or radial grooves (Figure 7).

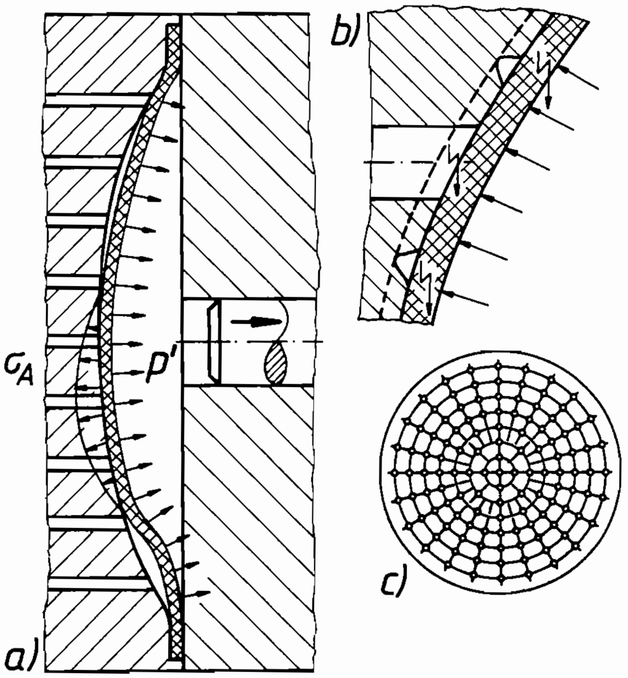


Figure 7. Diaphragm and Adhesive Forces: a) superload by local adhesion; and b) c) surface profile (metal diaphragms).

Underpressure Safety

All hydraulic drive systems for diaphragm pumps presently known are sensitive to long term suction side underpressure, regardless of the system used for replenishment of hydraulic losses. If suction side underpressure persists or occurs frequently, i.e., during standstill intervals, the hydraulic fluid will be aspired slowly into the hydraulic system along the piston clearance (forward leakage) and through the snifting and air bleed vent valve. The diaphragm gradually bulges more and more towards the fluid side and may become overstressed or damaged by being forced against the forward surface of the working chamber by the first stroke after restart.

Attempts to protect the diaphragm can be made by spring forces (which result in additional loading of the diaphragm as a disadvantage), by providing a safety stop for the diaphragm by means of a support disk with axial holes (Figure 4 (c)), by incorporating a specially shaped circular area supporting the diaphragm (Figure 8), by a coupling and sensing piece (Figure 9), respectively, by the total exclusion of underpressure conditions by monitoring the suction pressure level and taking suitable provisions to prevent such conditions.

All concepts providing a mechanical stop for the diaphragm may, however, involve the danger of local wear on the diaphragm if the fluid regularly or by chance contains particles. In

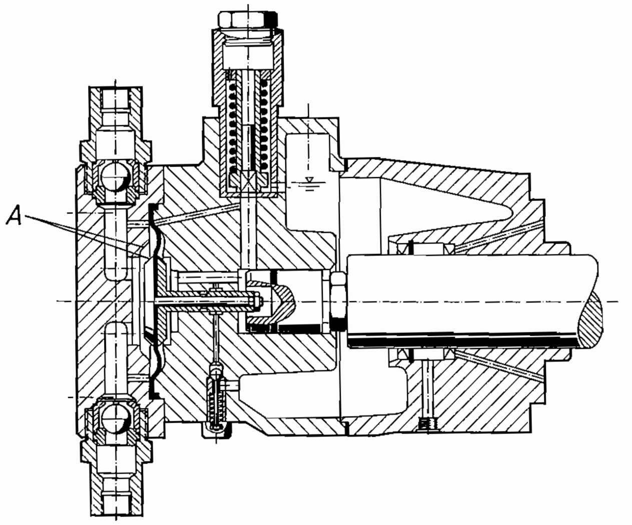


Figure 8. Diaphragm Control by Supporting Area.

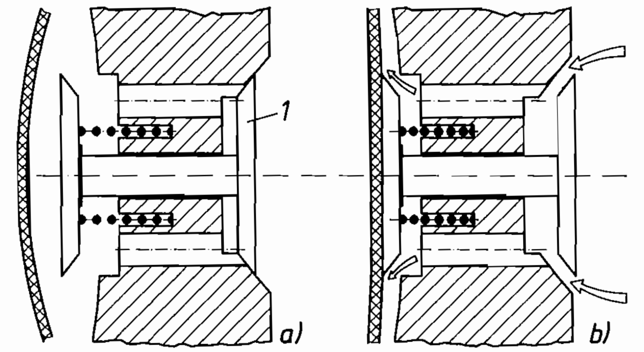


Figure 9. Diaphragm Control by Coupling Gate

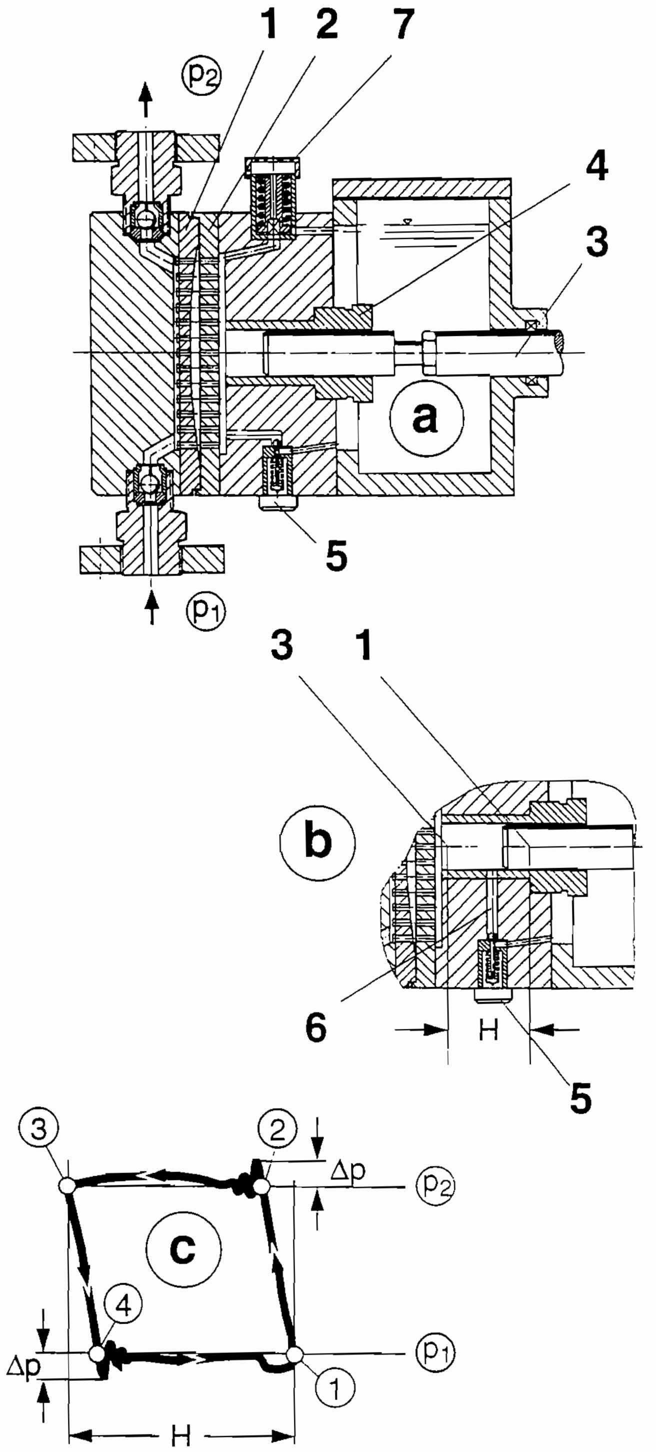


Figure 10. Diaphragm Underpressure Control (DUC): a) principle function DUC; b) DUC with additional sliding gate control by the plunger; c) indicator diagram; and 1,2 hole plates; 3,4 plunger, plunger seal; 5 snifting valve; 6 relief valve; 7 connecting bore.

plants where underpressure on the suction side can be dependably prevented and where the diaphragm is deflected forward and backward, startup valves (Figure 4 (b), item 6) are used. They open a temporary bypass passage in the hydraulic system (Figure 4 (b), item 7) during startup of the pumps, forcing the diaphragm into the correct position.

In pumps with metal diaphragms (low deflection, special applications), the support disk concept for diaphragm underpressure control (DUC) and safety is generally used (Figure 10). The working space is designed slightly larger than the displacement volume of the diaphragm. Therefore, the diaphragm will normally deflect into the vicinity of the front surface of the support disk, but not touch it periodically (as this is the case in diaphragm compressors for gases).

The snifting valve (Figure 10, item 5) responds in case of underpressure in the hydraulic system, i.e., in the rear dead center position of the diaphragm (underpressure caused by backward leakage of hydraulic fluid into the reservoir). To avoid erroneous replenishment of hydraulic fluid caused by spikes of low pressure on the suction side simulating fluid leakages, the piston can be simultaneously used as control valve (Figure 10 (b), item 6).

Installation/Diaphragm Interaction

Contrasting with the conditions existing in mechanically actuated diaphragms, the balance of the hydraulic forces in the hydraulically actuated diaphragm designs allows them to be relatively unaffected by pressure fluctuations or pulses, as long as the hydraulic system of the pump remains undisturbed.

In case of large pressure fluctuations (Figure 11) caused by pressure shocks or resonances in pressure pulsations however, the pressure amplitudes may exceed the setting of the hydraulic

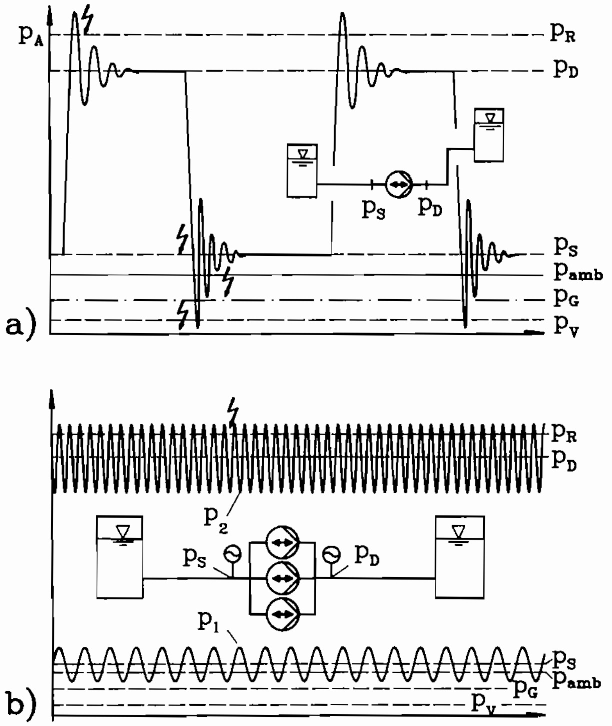


Figure 11. Installation/Diaphragm-Interaction; a) simplex pump (phase-cut by high discharge pressure); and b) triplex pump (resonance situation of pressure pulsations).

relief valve p_R or drop below the vapor pressure p_v of the fluids involved. Disturbances will result, such as

- the relief valve opens frequently ($p_A > p_R$),
- the diaphragm experiences locally excessive stress ($p_A \le p_V$, cavitation with shocks resulting from implosion of the vapor bubbles), which reduce the service life of the diaphragm.

Furthermore, the process fluid pressure in the pumphead should not fall substantially below the snifting valve pressure setting. This facilitates proper snifting valve operation and keeps degassing of the hydraulic fluid to a minimum. If pumps with hydraulically actuated diaphragms are used, it is highly advisable to perform a pulsation study (API 674) covering the system installation to detect such disturbances early and to suppress them by suitable dimensioning of the system or by the additional installation of dampers and/or filters [7, 8, 9].

THE DIAPHRAGM—THE HEART OF THE PUMP

Within the loads as determined by the entire system (see chapter 3) the diaphragm is expected to meet the required service life (> 10,000 h) in a compact design and a wide range of compatibility with different fluids and fluid temperatures. Considerable potential for improvements and further developments still exists (Figure 12).

Diaphragm Materials and Clamping

The properties of the materials predominantly used for diaphragms are compared in Table 1, clearly indicating the large differences in the modulus of elasticity, which is very important for the longterm deflection.

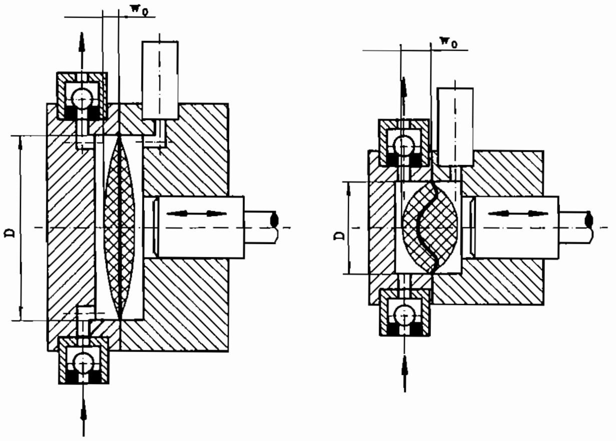


Figure 12. Reduction of Pump Size by Optimal Diaphragm Design.

Table 1. Diaphragm Materials.

	metals M	plastomers PTFE	elastomers EL
modulus of elasticity	2,1 x 10^5	700	5 - 20
strain properties	-	+	++
chemical resistance	++	++	o
thermal resistance	++	+	o
strenght	++	o	o
shape stability	++	-	++
elasticity	--	o	++
notch sensitivity	--	++	-
permeation tightness	++	o	+

Metal diaphragms consist of cold rolled sheets (thickness 0.2 to 0.5 mm) of austenitic chromium-nickel steels, respectively, and other metals or alloys with appropriate corrosion resistance (hastelloy, titanium, etc.). Cold rolling assures high strength and good toughness of the material. Until recently, due to ease of manufacture, disk shaped parallel-plane diaphragms are used.

In addition to the cases requiring better chemical resistance than that of PTFE, there are applications requiring elevated thermal resistance (up to 500°F/260°C, limited only by thermal stability of the hydraulic fluid) and high mechanical strength, a favorable property as far as clamping is concerned (Figure 13). These are the prime reasons for using metal diaphragms. Metal diaphragms are always clamped directly at up to 70 percent of the yield strength. The absolute absence of pores represents another important reason for using metal diaphragms (zero permeability).

To avoid fatigue in continuous service, metal diaphragms must only be stressed within the elasticity range, for the service life with respect to material fatigue decreases dramatically if 0.2 percent yield strength is exceeded. At the same time, as higher strength materials are used, they become very sensitive to notches (brittle).

PTFE diaphragms are usually cut out of sheets foils (with typical thickness of 0.020 in/0.5 mm to 0.080 in/2 mm) peeled from sintered blocks of the material. The mechanical properties of the sintered material depend on the polymer chain length, the size of the polymer particles, the manufacturing process, the sintering procedure and the crystallinity of the material. The diaphragms are used in parallel plane or thermally pressed undulation formats.

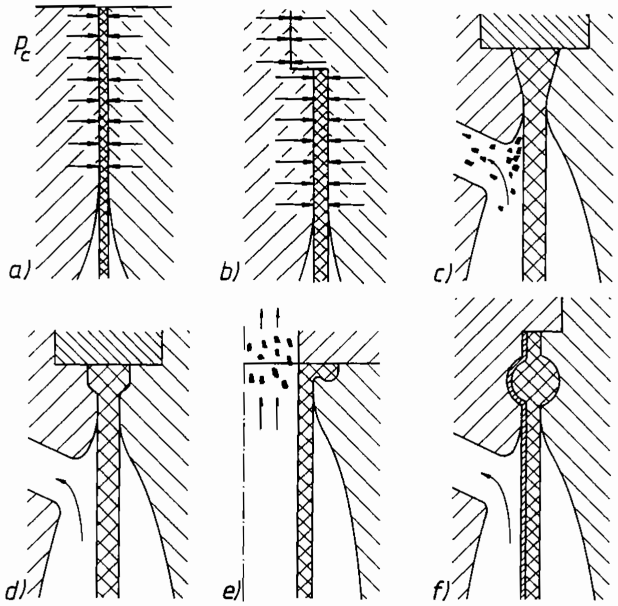


Figure 13. Various Clamping Features: a) direct (metal); b) shunt force (restricted compression, plastomer); c) d) various clamping geometries (elastomer); e) tube diaphragm (elastomer); and f) O-ring profile (PTFE lined elastomer).

Their typically superior chemical resistance, together with good resistance to heat (up to a limit of approximately 300°F/150°C) are the prime reasons for popularity of PTFE diaphragms.

The properties concerning mechanical strength are determined by the viscoelasticity of the material. At any level of stress PTFE deforms, to a large extent in plastic fashion (nonlinear, Figure 14) and shows a tendency towards creeping, which is time dependent and gradually lowers stress conditions (Figure 14, detail K). For this reason, PTFE is comparatively insensitive against notches. Even under dynamic loads, the stress peaks of tension are reduced by means of local plastification. Accordingly, this viscoelasticity forms a favorable property in the face of the loads acting on the diaphragm. Other possible materials for diaphragms from the field of plastomers, such as ultra high molecular polyethylene (PE-UHM) are only advantageous in isolated cases.

Due to its sintered structure, PTFE always exhibits some amount of permeability, which can be reduced to technically acceptable low levels by proper selection of the size of the particles, the manufacturing process and sufficient thickness of the diaphragm.

Clamping of PTFE diaphragms is performed mostly with shunted forces (using the principle of limited compression, Figure 13 (b)) acting on sufficiently large clamping areas. By means of grooves in the clamping areas lip type sealing effects and local stops against creeping due to viscoelasticity can be created.

Following the assembly of PTFE diaphragms into pumps, the diaphragms obtain their final operational shape by plastification during the first cycles of actual operation. The stresses performing this initial deformation always exceed the range of elasticity. Thanks to the viscoelasticity, PTFE can carry relatively high elastic/plastic dynamical strains with a high level of endurance.

Elastomer diaphragms are mostly hot molded, diskshaped, undulated parts, frequently in a multilayer design (with thickness > 0.10 in/3mm) and also often with reinforcing fabric. Typically, the elastomers, acryl-nitril rubber (NBR), ethylen-propylen-dien rubber (EPDM), butyl-rubber (IIR), fluor-rubber (FRH), have significantly lower resistance to chemicals and heat as compared with PTFE, but are impermeable and fairly dimensionally stable.

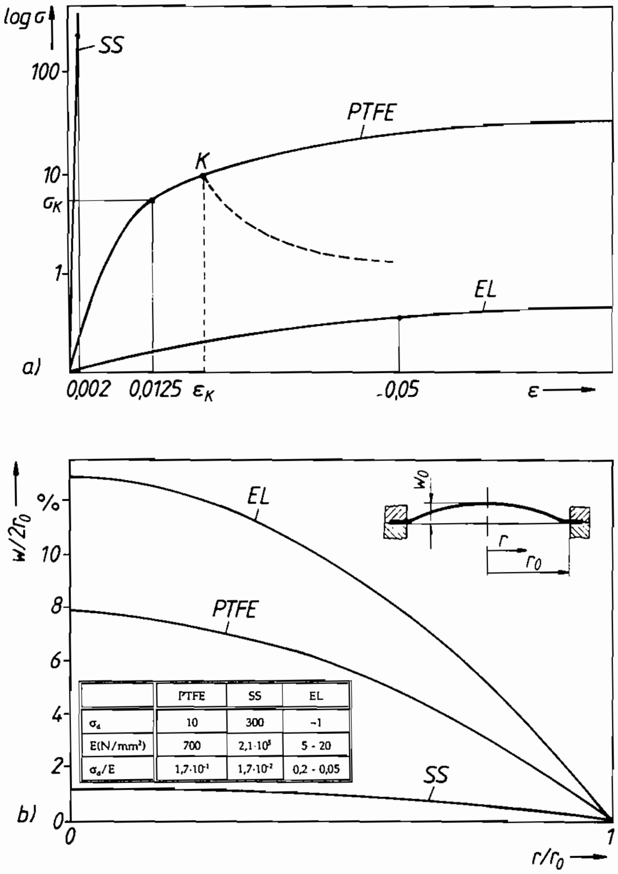
The high tolerance for elastic deformation and, consequently, a large displacement intensity represent the principal reasons for the use of elastomer diaphragms. For a number of reasons, this potential can unfortunately be used for limited process applications. Elastomers are sensitive to notches (stresses at local edges, notches and sharp angles), show limited resistance to chemicals and heat, and, in typical applications, require a multitude of different material types have be kept in stock to meet application specific requirements.

Elastomer diaphragms are always clamped with shunted forces and feature lip, wedge, or O-ring shaped cross sections in the clamping area (Figure 13, item c and d). Tube type diaphragms are feasible and offer operational advantages in the delivery of slurries (Figure 13, item e). Coating elastomer diaphragms with PTFE has some potential for further investigations and future applications. However, in the face of the low thickness of the layer of PTFE (< 0.020 in/0.5 mm), the porosity turns into a problem and limits the applications.

Material Selection

The principal criteria in the selection of diaphragm materials are:

- the resistance to chemical attack and to heat,



	PTFE	SS	EL
σ_d	10	300	~1
E(N/mm²)	700	$2{,}1 \cdot 10^5$	5 - 20
σ_d/E	$1{,}7 \cdot 10^{-1}$	$1{,}7 \cdot 10^{-2}$	0,2 - 0,05

Figure 14. Stress/Strain Correlation (A) and Deflection Potentials of Plane-Parallel Diaphragms (SS Stainless Steel, PTFE Polytetrafluorethylene, El Elastomer).

- the maximum allowable deflection of the diaphragm (high displacement intensity).

In sealless diaphragm pumps for industrial processes, PTFE diaphragms are presently the most widely, since they offer a maximum of displacement intensity, and chemical and thermal resistance. Figure 14 (b) shows an example of parallel plane diaphragms. The diagram is based on parameters experience has shown being tolerable for long term strain during dynamic loads: SS 0.2 percent, PTFE 1.25 percent, EL 5.0 percent.

Additional criteria for entering the selection procedure are:

- capability for cleaning.
- capability for sterilization.
- tightness.

Presently, the potential for developments in the field for diaphragm materials is largely exhausted. Attempts to improve the performance must, therefore, concentrate on the optimization of the shape of the diaphragms.

Potential for future developments still exists in the field of quality assurance. Particularly for PTFE, careful analyses of the production and preparation parameters offer room for improvement.

Diaphragm Design

Within the range of requirements, safety considerations are paramount for sealless process pumps. In diaphragm design, sandwich configurations—double wall barriers, provide the ultimate in safety with: redundancy, true secondary containment, and diaphragm condition monitoring. The optimal design of diaphragms, therefore, is dominated by the quest for:

- long service life.
- high displacement intensity.
- safe operation.

Diaphragm Shape and Clamping—Sandwich Design

During direct or shunt type clamping, the applied compression results in radial extrusion of the diaphragm material (Figure 15 (a)) and accordingly, results in the real installed shape of the diaphragm. Parallel plane diaphragms assume, for example, a shallow domed shape and actually only reach this by deformation to their appropriate degree of displacement intensity.

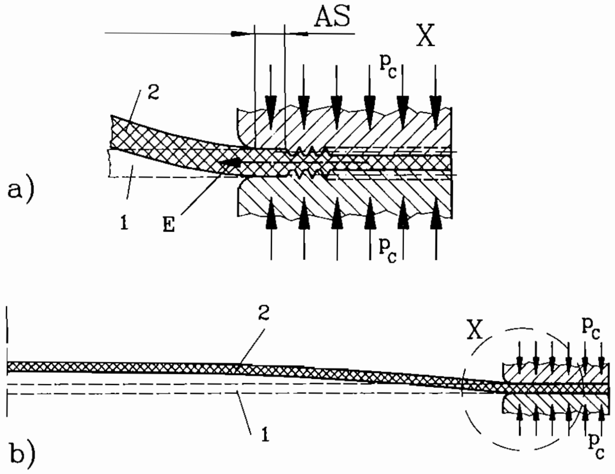


Figure 15. Diaphragm Deformation by Clamping Extrusion: 1) initial; 2) after clamping; and (E) Extrusion.

Sandwich type diaphragms require careful design of the details of clamping (Figure 16) since, in addition to hermetic sealing, attention has to be paid to the signalling channel towards the pressure sensor to avoid any obstructions, and to assure the dependable operation of this important safety device.

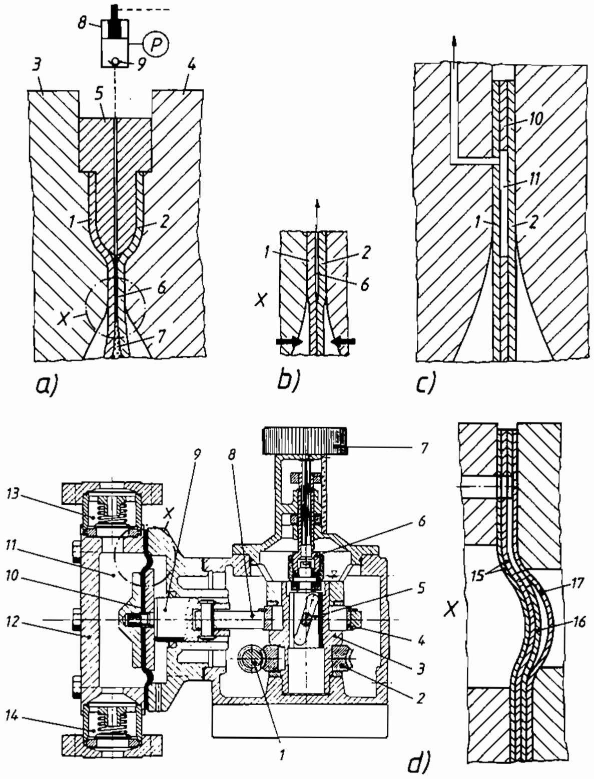


Figure 16. Sandwich Diaphragms: a) hydraulically driven PTFE diaphragm; b) after compression coupling; c) hydraulically driven metal diaphragm; and d) mechanically driven PTFE diaphragm.

For hydraulically actuated PTFE diaphragms, a configuration (Figure 16 (a)) is suitable. Following assembly, the two sheets of the diaphragm are coupled by the pressure acting on them and eventually by an auxiliary inner fluid (Figure 16 (b)). The passage (item 6) to the sensor (nonreturn valve + pressure sensor, items 8) and 9)) must remain unobstructed. The clamping has to be designed to assure dependable function and response of this important safety and maintenance related feature.

For hydraulically actuated metal diaphragms, a fine slot (item 11) in the central diaphragm (item 10) offers the only solution, in most cases. This slot should, however, interfere as little as possible with hermetic clamping of the diaphragm assembly or affect the operation and service life of the diaphragm.

For mechanically actuated PTFE diaphragms, a multiple layer sandwich-configuration as shown in Figure 16 (d) proves to be optimal. The two active layers (item 15) with a slotted layer in between and a normally unloaded layer (item 17) are combined into a package. The normally unloaded (redundant) diaphragm serves as a temporary safety barrier in case both of the two active diaphragms suffer any loss of integrity.

Diaphragm Stress

Different concepts for the shape of the diaphragms (Figure 17) result in specific loads and stresses to which the diaphragm is subjected. It should be noted that a plane diaphragm as shown in

Figure 17 (a), widely used due to its simple production, assumes the shape of a shallow calotte after installation and the first operational strokes.

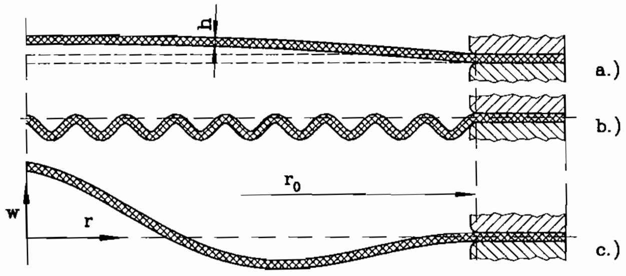


Figure 17. Diagram Design Features.

Parallel plane diaphragms are mainly subjected to biaxial membrane stresses. Particulary in the clamping area, however, uniaxial stress due to flexing dominates (Figure 18 (a)).

In undulated, or corrugated, diaphragms the deformation of the diaphragm is transferred to bending of the undulations, which results in lower stress at the outer circumference (Figure 18 (b)).

In case of plus/minus deformation of the diaphragm, the stress at the clamped rim is alternating. Furthermore, all bending stresses are alternating, while the socalled membrane-stresses however remain pulsating only. In undulated diaphragms for plus/minus deformation, the tangential stresses develop alternating additionally.

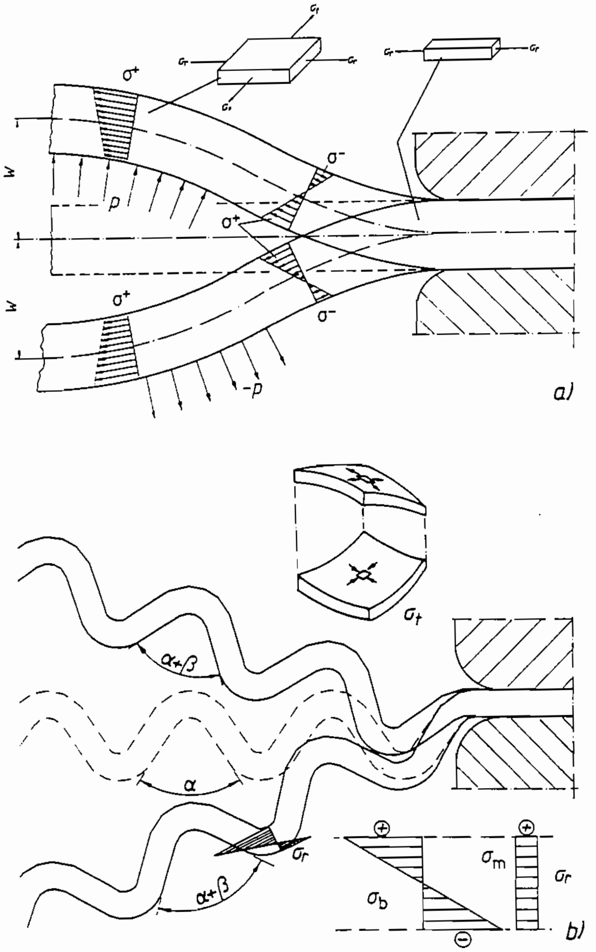


Figure 18. Stressing Planeparallel (A) and Undulated (B) Diaphragms.

The "zero transition" of the diaphragm merits special attention. Parrallel plane diaphragms (already conditioned into the domed shape) can pass through this situation with only transitional (partial) buckling (Figure 19). As practice has proven, stress levels large enough to induce ruptures may occasionally occur during these passages. In sandwich type diaphragms, the stress levels are in a somewhat better position for stable zero transitions due to their radial elasticity.

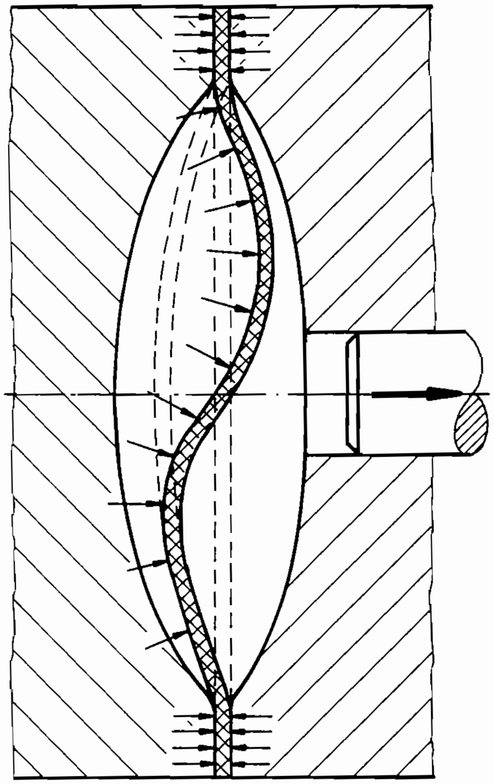


Figure 19. Buckling at Zero Transition (Schematical).

For the design of diaphragms not experiencing fatigue, the following remarks concerning specific properties of the applied materials should be added:

The design of metal diaphragms is based on the "theory of flexible plates" [11], using the characteristic fatigue limits for the metal sheets. In freely flexing diaphragms used for sealless process pumps, high bending stresses ocurring mainly at the rim (Figure 20). During normal operation, frontal supports are shunned, since disturbances may result from adhesion of the diaphragm to the surface. Some potential for future developments still exists in the field of suitable rim area support. In this context, attention has to be paid to local notch stresses caused by impressed particles, as cold rolled sheet metal is quite sensitive against notches (Figure 21, a case of actual damage shown in Figure 22). For metal diaphragms, buckling during zero transition, respectively, at surfaces the diaphragm rests against, should be avoided [12].

Until recently, the design of PTFE diaphragms was only carried out empirically, as permitted by the favorable properties of PTFE. Suitable methods for computation of the occurring

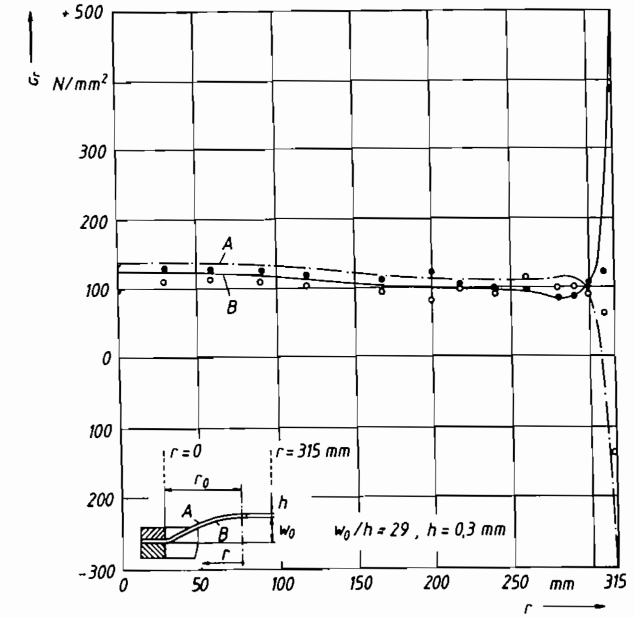


Figure 20. Maximum of the Radial Stress σ_r *of a Free Flexing Metal Diaphragm, Calculation (Full Lines), Measurement (Dotted Lines) [11].*

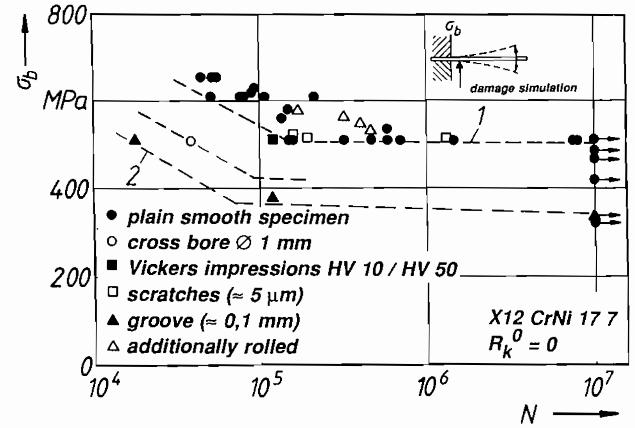


Figure 21. Fatigue of Stainless Steel Sheet Material at Various Notch Effects: 1) smooth, 2) notched, and N) number of cycles.

stresses were not available and knowledge about the values for permanent strength of PTFE were nonexistent.

According to recent investigations [13], the occurring stresses can be determined by means of the method of Finite Elements (FE) and the use of nonlinear characteristics of the materials (Figure 23).

Some relevant techniques are:

- two-dimensional rotationally symmetric grid structure,
- structuring of the FE-elements in four layers, and
- implementing of the clamping and contacting problems.

Experimental measurements of the deformations occurring verify the results of the computations. Also, according to recent investigations [13, 14] further characteristic data for the "fatigue limit" of PTFE can be determined by means of hysteresis measurement. In this precedure, the stress in a specimen of the material is increased in steps, each time following several hundred load cycles (Figure 24 (a)).

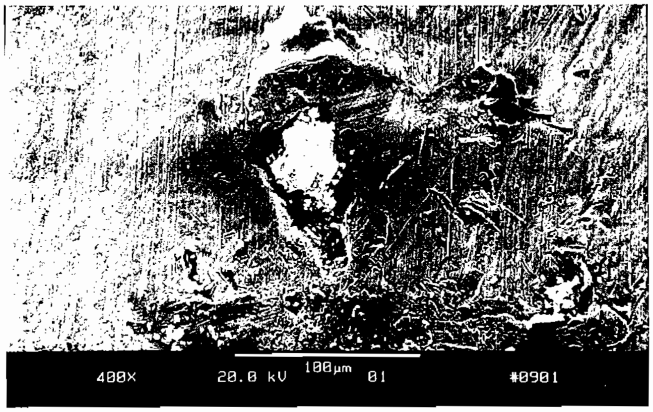


Figure 22. Failure of a SS Diaphragm by Notching Effect through a Sand Particle (Rupture after 2500 h, 600 Bar).

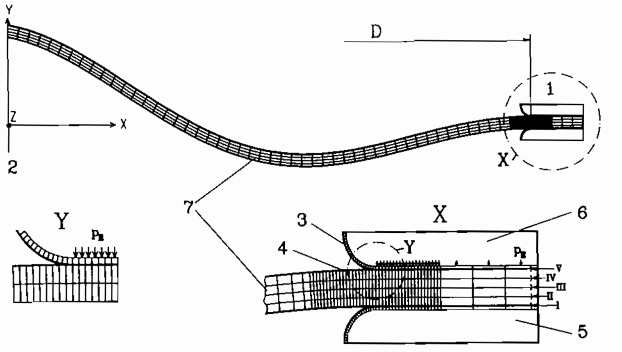


Figure 23. Two-Dimensional FE Network of a Clamped Undulated Diaphragm: 1) clamping ring; 2) diaphragm center; 3) contact line; 4) contact elements; 5/6) clamping comtour; 7) diaphragm; and 8) plane of the nodes.

The typical phase shift between stress and strain of viscoelastic materials is the basis of the hysteresis method. The stress/strain cycle yields a hysteresis loop (Figure 24 (b)). The maximum stress/strain is derived as shows Figure 24 (c). The "fatigue limit" results from two intersecting straight approximation lines. For a certain PTFE-type, the method yields longterm permissible pulsating stress of about 1015 lb/in^2 (7N/mm^2) and as alternating stress of about 800 lb/in^2 (5-6N/mm^2).

While steels experience fatigue for pulsating and alternating stresses, the fatigue properties of PTFE have proven to be different. As explained earlier, the relaxation properties of PTFE avoid perforation at a specific strain by the self reduction of the stresses. This can be applied to dynamic load also, and explains the experimental experience that pulsating stressing at constant strain, which is characteristical for pump diaphragms, does not exhibit noticable fatigue. With alternating stressing however, the relaxation due to change in sign (+ to -) of strain is compensated during each cycle. Consequently, alternating stressing of PTFE is not time-dependent and, therefore, more critical. Experimentally, this was confirmed with various diaphragm shapes experimentally during fatigue tests.

Bending at the Clamping Rim

The large uniaxial strain, characterized by the rim contour of the clamping components, is normally alleviated by a moderate

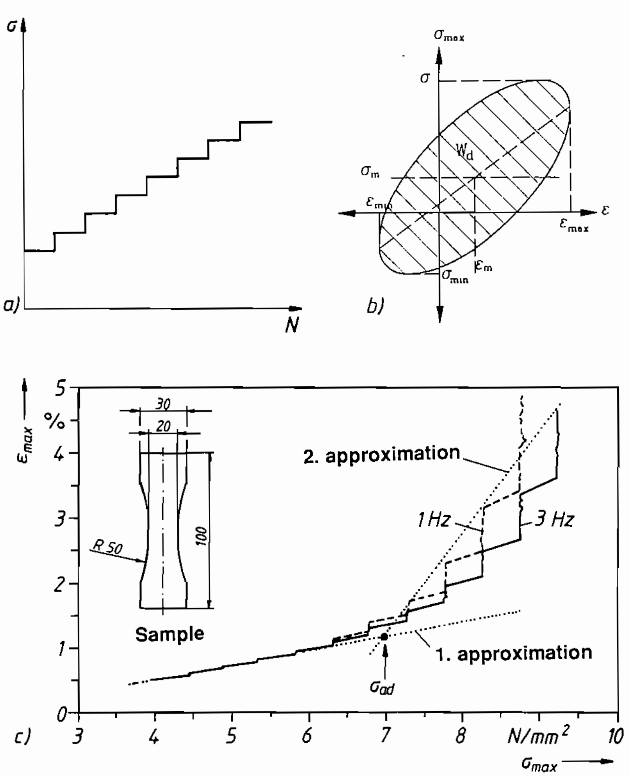


Figure 24. Characterization of PTFE at Dynamic Load Conditions: a) b) hysteresis method; and c) determination of admissible stress σ_{ad}

radius (r = ca 0.040 in/1.0 mm, to avoid particle sedimentation). The strains in that area of the diaphragm, which regularly exceed the plastification range of PTFE, reveal a remarkable behavior of the material; a so-called yield hinge is created and, thus, the high strain at the clamping rim can be handled without fatigue. In the area of the yield hinge the macromolecules assume a special orientation and, consequently, superior dynamic strength, most probably due to the change from a spherolitic to a fibrel structure [15], which can be clearly recognized in Figure 25. This phenomenon obviously is the key for the adequate understanding of the outstanding endurance of plan-parallel PTFE diaphragms.

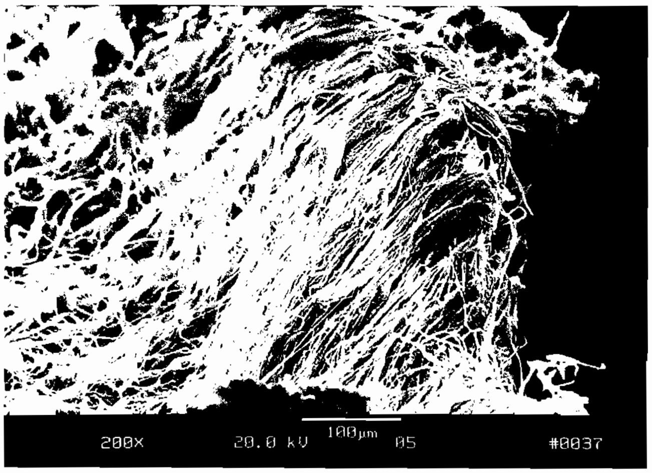


Figure 25. Fibral Structure in the Ruptured Cross Section of a Yield Hinge with PTFE.

OBJECTIVES OF THE DIAPHRAGM SHAPE DEVELOPMENT

The potential for optimization potential seems mainly to be concentrated in the area of the shape design. Plan-parallel types offer only minor possibilities, but undulated types offer a much broader range of possibilities for improvment. Research toward the optimum design should be directed at variation in number and amplitude of the undulations.

With mechanically actuated diaphragms, the support stabilizes the diaphragm shape and a single, large, convolution is most desirable.

The potential for further development centers around the undulation geometry and the clamping areas, especially concerning the rigid central diaphragm support.

With hydraulically actuated diaphragms, local elastic domes are created by the forced deflection towards the end of the diaphragm travel. The deflection resistance of the diaphragm requires a certain deformation pressure. If an undulation exhibits insufficient stiffness, the dome contour is locally buckled (Figure 26). This procedure develops with minimal energy, which means that buckling starts at one location (or several places at the same time) implementing a collapse and the larger danger of perforation. The reason rotationally symmetrical undulated diaphragms buckle, is exessive tangential compression stress. The same effects may occur when nonsymmetrical zero transition combined with increased deformation pressure. The buckling behavior of various diaphragm shapes is definitely influenced by diaphragm thickness, radii of the undulations and their locations, with undulations at larger diameter positions being more endangered.

As a consequence, nonbuckling and safe diaphragms for hydraulical operation require a moderate number and amplitude

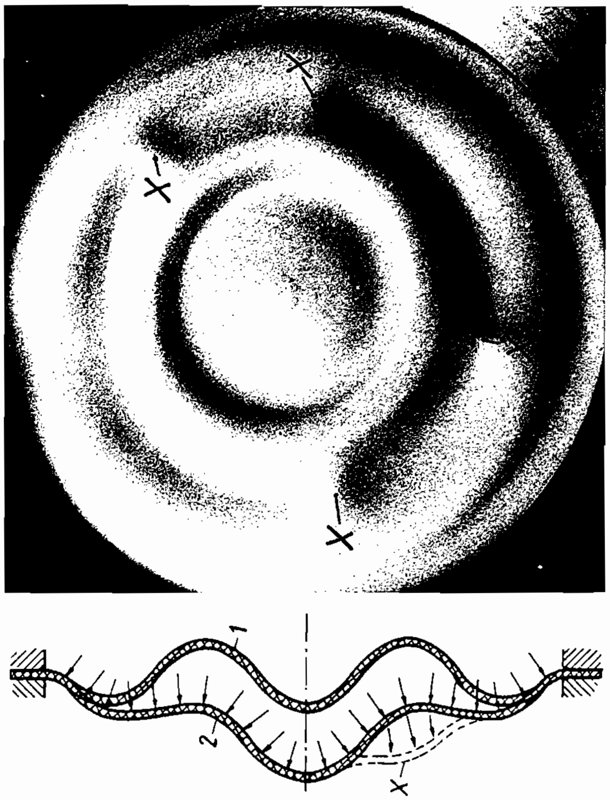


Figure 26. Local Buckling of Diaphragms. 1) inital; 2) deflected, and X) buckling locations.

of undulations. More undulations avoid buckling but implement the danger of fatigue. The optimum diaphragm has to work in the narrow window of nonbuckling and nonfatiguing geometry.

The investigation of many diaphragm features (Figure 27) demonstrate further development towards geometries which are stable in shape and with low stresses for longterm endurance. Transferring the philosophy into new pump series may be on one hand, larger displacement intensity and smaller dimensions, or on the other, only increased safety.

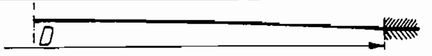
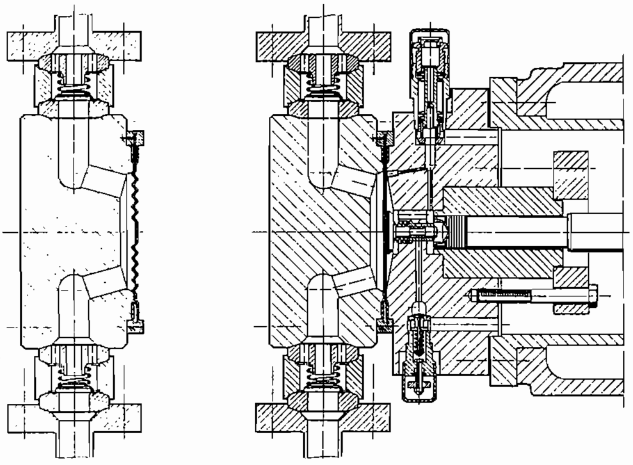
Diaphragm shape (D/s = 100)	failure
	b
	b
	f
	f
	f
	f
	f
	b

Figure 27. Comparision of Failure Reasons of Various Diaphragm Features. b) buckling, and f) fatigue.

ECONOMY, PERFORMANCE, DURABILITY

Good reasons for the application of diaphragm pumps are the requirements for sealless pumps and the avoidance of troublesome, dynamic plunger seals. The convincing advantages, as explained earlier, have increased the market share of diaphragm pumps remarkably, although capital investment is higher. This is more than compensated for by the vastly superior economy of diaphragm pumps with respect to lifetime expenses compared to piston/plunger pumps. In the current market, mechanically actuated diaphragm pumps are available at a comparable investment to that of plunger pumps (Figure 16 (d), left). Multilayer, PTFE-sandwich-diaphragms, cope with all process requirements and have demonstrated diaphragm lifetimes exeeding 10,000 hr.

The hydraulical actuated PTFE diaphragm, for comparison, has demonstrated possible lifetimes of well over 20,000 hr. Modern high performance diaphragm pump concepts utilize parallel-plane and undulated diaphragm, and various PTFE compounds, in order to take advantage of their special features on an individual case by case basis (Figure 28). High pressure diaphragm pumps with metal diaphragms up to 11,600 psig (800 bar) discharge pressure may now be equipped with sandwich diaphragms too, so that the whole application range for sealless process diaphragm pumps can meet the highest safety demands (Figure 29).



b) a)

Figure 28. Liquid End of a Large Process Diaphragm Pump (300 Bar). A) plane parallel diaphragm, and B) corrugated diaphragm.

To overcome high temperature limitations (> 500°F/260°C), it is a good solution to apply remote head designs of diaphragm pumps. The motive (diaphragm) head is situated below the valve head, in order to keep high temperature fluid away from the PTFE diaphragm. The fluid in the cooled connection pipe between both heads is acting as a hydraulical linkage.

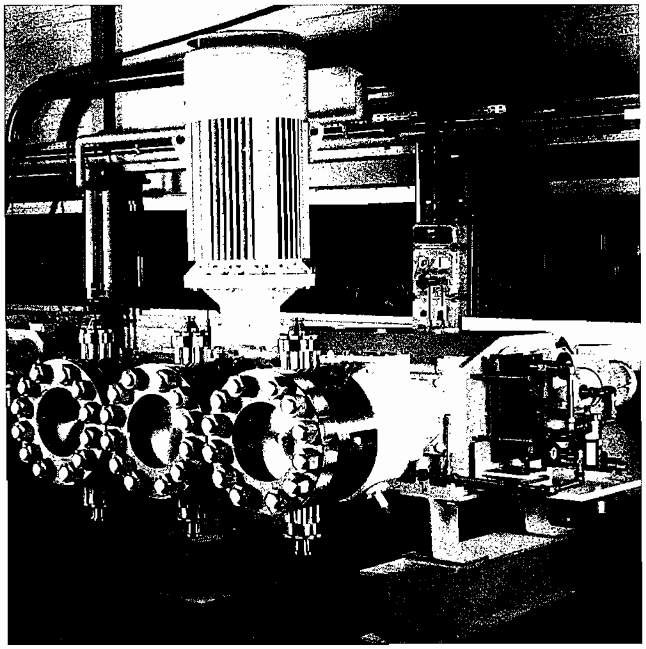


Figure 29. Triplex Diaphragm Pump for an Injection System Offhore (LEWA, 500 Bar, Metal Diaphragm).

Recently, a new generation of diaphragm pump head technology, for the ranges of up to 4.4 gpm/1.0 m³/h and up to 870 psig/60 bar, has been introduced (Figure 30). It combines the superb existing DPC technology with a diaphragm support area (Figure 8). Normally, the diaphragm deflects without touching the front surface of the working chamber. Only external disturbances can cause the diaphragm to contact the surface temporarily. Another important feature is to guide the diaphragm in order to avoid any buckling effects and to realize long lifetime.

This design concept signals the start of the next generation in diaphragm pumps and provides the additional benefits of improved safety an reliability [16, 17, 18].

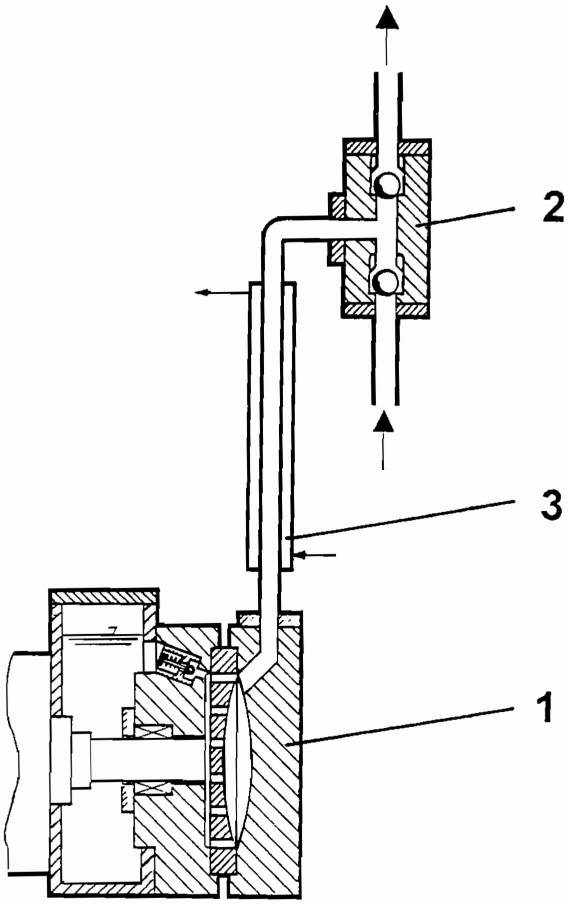


Figure 30. Remote Head Diaphragm Pump.

CONCLUSIONS

The successful introduction of process diaphragm pumps into the sealless process marketplace will continue due to the impressive advantages the system offers.

The application areas of mechanically or hydraulically actuated diaphragm systems are becoming more and more clear. The mechanically actuated diaphragm technology has seen major progresses to cope with the ever increasing process requirements.

Diaphragm design has to take care of the fact that the diaphragm is part of the entire system. As mechanically actuated diaphragms are loaded by the pressure differential, they will remain limited to lighter duty applications. The hydraulically actuated diaphragms may be applied for all requirements; since they are the only means by which to achieve sealless diaphragm process pumps for larger capacities and higher pressures.

The diaphragm control systems should keep the diaphragm apart from the working chamber surfaces under normal operating conditions in order to avoid any damages. On the other side, future systems that offer real safety functions for the diaphragm when external disturbances occur (i.e., by pump/piping interaction) will be preferred.

Diaphragm development seems to have exhausted the potential material selection: metal, polytetrafluorethylene (PTFE) and elastomers. The predominantly applied PTFE needs very careful design, especially at the clamping area, in order to cope with the viscoelastic properties. The futher optimization of diaphragms has to head for improved shape design with regard to fatigue safety and displacement intensity. The future chances are very good for PTFE diaphragms as finite-element-stress analysis is available now for nonlinear viscoelastic materials, too. The hysteresis measurement method continues to offer a better understanding of the fatigue properties of PTFE compounds.

The optimal diaphragm shape and displacement must be situated in a narrow window between buckling and fatiguing. The available options look very promising, whether it is for developing smaller diaphragm pump dimensions or superior safety.

In actual fact: actual application experience, economic pressures and future challenges keep the diaphragm development an exciting story.

NOMENCLATURE

Symbol	*Unit*	*Designation*
D	mm	diameter of diaphram
d	mm	diameter of plunger
E	N/mm²	modulus of elasticity
F_H	N	hydraulic force
F_R	N	rod force
F_C	N	clamping force
H	mm	stroke
h	mm	thickness of diaphragm
N	-	number of loading cycles
n	-	number of cycles
p	bar	pressure
p_A	bar	working space pressure
p_{amb}	bar	atmospheric pressure
p_D	bar	discharge pressure
p_C	bar	clamping pressure
p_G	bar	degassing pressure
p_R	bar	pressure setting of the relief valve
P_S	bar	suction pressure
P_V	bar	vapor pressure
p'	bar	pressure on diaphram rear surface
p''	bar	pressure on diaphram front surface
p_1	bar	pressure at the suction side
p_2	bar	pressure at the discharge side
Δp	bar	pressure difference
Δp_M	bar	maximum of pressure difference
r	mm	radius
r_0	mm	radius of the diaphram working chamber
$\dot{V}$	m³/s	volume flow
W_d	J	energie of dissipation
w_0	mm	maximum of diaphragm deflection

ε	-	strain
ε_{max}	-	maximum of strain per load-cycle
ε_{min}	-	minimum of strain per load-cycle
σ	N/mm$_2$	stress
σ_A	N/mm$_2$	adhesive stress
σ_{ad}	N/mm^2	admissible stress
σ_b	N/mm$_2$	bending stress
σ_d	N/mm$_2$	fatigue stress
σ_m	N/mm^2	mean stress
σ_{max}	N/mm^2	maximum of stress per load-cycle
σ_{min}	N/mm^2	minimum of stress per load-cycle
σ_r	N/mm^2	radial stress
σ_t	N/mm^2	tangential stress
σ^+	N/mm^2	tensile stress
σ^-	N/mm^2	compressive stress

AS	area without scoring
EL	elastomer material
M	metals
PTFE	Polytetraflourethylen
SS	stainless steel

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