A CONTEMPORARY GUIDE TO MECHANICAL SEAL LEAKAGE

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ABSTRACT

The mechanical seal is a critical component in many mature industrial processes such as flue gas desulpherization, crude oil transport and refining, electricity production, and pharmaceutical manufacturing. A "critical component" can be defined as one that can reduce plant output significantly or even halt it completely if the intended performance of the component is compromised.

Mechanical face seals have evolved from critical components to "enabling technologies" in contemporary applications such as multiphase pipeline transport, synthetic production of proteins and enzymes, ultra-high-speed centrifugal compressors, and many exotic chemical processes that take place at extreme pressures and temperatures. An "enabling technology" is one without which the application could not be realized.

With such a high population of *critical component seals* and *technology enabling* seals worldwide, a modern contextual review of the physical meaning of seal leakage, underlying theoretical governing formulas, typical ("order of magnitude") leakage values and trends of different seal designs, and the effective limits of seal leakage is more than warranted. The intention here is to create a comprehensive reference work that has global applicability and is based both in practical experience and sound theory.

INTRODUCTION

"How much *should* this seal leak?"

"How much *can* this seal leak before it becomes a problem?"

"The seal is leaking. Should I remove it from service?"

These are questions posed to mechanical seal manufacturers every day. Seal users have realized that the answers to these questions are complex and often lead to even more difficult questions. In many cases it is the user that can best answer their own questions. Ideally, a strong relationship with the seal manufacturer as a partner rather than a commodity supplier will address these issues before the seal is placed into service.

A discussion of mechanical seal leakage can be organized by those factors that limit leakage in various ways. These can be separated into five general categories:

1. Leakage limited by *law*

2. Leakage limited by *process*

3. Leakage limited by *housekeeping*

4. Leakage limited by *support system*

5. Leakage limited by *engineering design standard*

In some cases the end user may have detailed and evolved expectations of seal leakage. This is often the case at mature petrochemical refineries where governmental regulation of emissions has been in effect for nearly 20 years. The first category, leakage limited by law, is typically of paramount importance to end users so that they do not incur fines, operational injunctions, or an erosion of public confidence both in their neighborhood or on the relevant stock market.

The second category, leakage limited by process, usually falls within the end user's expertise as well. Contamination of a process fluid by seal leakage can require further downstream processing, yield a less efficient reaction chemically or thermodynamically, result in a less commercially valuable end product, or even pose a safety risk.

Leakage limited by housekeeping also lies within the domain of the end user's knowledge. Often the geographic climate itself influences this as leakage freezes, evaporates, condenses, dries, or otherwise behaves in a way familiar to site personnel. Seal leakage may also prevent or hinder maintenance of other equipment in the area.

Responsibility for categories 4 and 5 are typically shared by the end user and seal supplier (manufacturer, distributor, original equipment manufacturer [OEM], or engineering contractor).

Each category shall be discussed in detail and offer up many issues for discussion before they become a problem. But realize that categorization as such only provides a convenient structure for analysis. In reality these issues are all quite intertwined into a system that behaves as a complex organism. That is precisely why end users and seal suppliers must all bring their experience to the table and listen carefully to one another, develop an agreed upon plan, then execute that plan daily in a disciplined manner.

THEORETICAL BASIS OF LEAKAGE

Before engaging in a discussion of seal leakage from a practical or procedural perspective, one must first gain solid footing based on physical phenomena and mathematical behavior of face seal dynamics. Mechanical seals rely on thin film lubrication in order to support axial loads in a low-friction regime at a film thickness that limits leakage as much as possible. Many sources derive the relationship that governs this effect for face seals (Lebeck, 1991; Panton, 1996). The final form will be presented of an equation derived from the Navier-Stokes equation for fluid flow with the appropriate assumptions and boundary conditions applied for thin film geometry. This is a form of what is referred to as the Reynolds equation:

$$\dot{m} = r_o \int_0^{2\pi} \rho(p) \left(-\frac{h^3}{12\mu} \frac{\partial p}{\partial r} \right)_{r=r_o} d\theta \qquad \textbf{(1)}$$

where:
h = Film thickness, m
$\dot{m}$ = Mass flowrate, kg/s
p = Pressure, Pa
r_0 = Outside radius of seal face, m
θ = Angle, rad
μ = Dynamic viscosity, kg/m–s
ρ = Density, kg/m^3

Equation (1) is valid for both liquids and gases, although the $\rho(p)$ term is generally a constant for liquids. The negative sign appears because the ∂p term is defined as inside pressure minus outside pressure. For outside pressurized seals, the ∂p term will be negative and cancel out the minus sign.

One can see that the relationship between leakage and seal radius, pressure drop across the seal face, fluid density and dynamic viscosity are all linear, with only viscosity inversely so. The relationship between leakage and film thickness is cubic, however. While the equation appears simple at first glance, one must understand that the film thickness, h, is itself a function of several variables:

$$h = h(\phi, u, R_a, h_w, \mu) \qquad \textbf{(2)}$$

where:
ϕ = Net radial taper of seal faces, rad
u = Relative velocity of seal faces, m/s
R_a = Average surface roughness of seal faces, µm
h_w = Amplitude of circumferential waviness, µm

Some of these variables are yet again a function of many other variables, and often functions of one another.

A casual review of the Reynolds equation might lead one to conclude that higher viscosity results in lower leakage, but that is only true under *static* conditions. The film thickness, h, is a strong function of dynamic viscosity, µ, and velocity, u. Increased dynamic viscosity results in a dramatic increase in hydrodynamic or aerodynamic lift. This function is typically highly nonlinear and must be solved using advanced numerical techniques during the analysis phase.

Other parameters of seal design, such as spring load, balance ratio, radial face width, face patterning or surface treatments, will not be discussed. None of those parameters changes the derivation and mathematical form of the Reynolds equation. Those parameters, rather, affect only the functions such as h and $\partial p/\partial r$ contained therein. A solid understanding of the Reynolds equation is therefore a prerequisite to understanding those more intricate design bases.

One often hears the statement, “All seals leak; they have to in order to work.” Look again at the Reynolds equation and think about this statement. Approach this statement in a different way. Assume that mass leakage approaches zero. For the Reynolds equation to be satisfied, one or more of the following statements must be true:

(a) $r_o \to 0$
(b) $\rho(p) \to 0$
(c) $h \to 0$
(d) $\frac{\partial p}{\partial r} \to 0$
(e) $\mu \to \infty$

For (a) to be true the seal geometry would cease to exist. For (b) to be true, the sealed fluid would not exist. For (c) to be true the seal faces would have to be perfect mathematical planes in perfect contact, which is entirely impractical. Condition (d) could exist, but then with no sealed pressure differential one asks why a seal is needed at all. One could argue that condition (e) could exist with a fluid of extremely high viscosity, like a polymer for instance. Practically speaking it is difficult if not impossible for such fluids to even enter the sealing interface. Even if the fluid could fill the sealing interface, leakage would approach zero only with zero rotation, as discussed above. Any rotation whatsoever would produce an extreme increase in h, resulting in leakage.

Based on this exercise, one could say that seals do indeed have to leak in order to function. But one needs to examine the orders of magnitude of the input variables to see what sort of leakage one is talking about. Assume the following application with water at 1.0 MPa (145 psi) and 35°C (95°F) as the sealed fluid:

h = 0.025 µm (1.0 µin)
dp = 1.0 MPa (145 psi)
r_o = 100 mm (3.937 in)
dr = 5.0 mm (0.197 in)
μ = 0.00072 kg/m–s (0.72 cP)
ρ = 1000 kg/m^3 (62.4 lbm/ft^3)

For this set of inputs one calculates:

$$\dot{m} = 1.82e-6\ kg/s\ (0.014\ lbm/h) \qquad \textbf{(3)}$$

Which is equal to only 6.5 mL/hr (0.22 fl oz./hr), or roughly 1.5 drops per min. An empirical variation of the Reynolds equation used by this author’s company yields 0.5 mL/hr (0.017 fl oz./hr), or roughly eight drops per hour. Evaporation of the leakage would render this measurement nearly impossible. One can perform these basic calculations for many different scenarios, but will reach a conclusion that only in very rare cases is visible, measurable liquid leakage required in order for a mechanical seal to operate successfully.

For seals that operate on a gas film, the basic statement that “leakage is required for stable performance” is essentially true. The Reynolds equation cannot be solved directly with hand calculations as was done in the previous example because both $\rho(p)$ and $\partial p/\partial r$ are nonlinear functions of other variables. But the Reynolds equation must still be satisfied!

PRACTICAL LEAKAGE VALUES

Seal manufacturers will provide estimated leakage values for many of their products when this is possible. Good examples of this are self-acting gas seals. But in many cases there are just too many variables that render anything more precise than an order-of-magnitude statement impractical. Several factors influence mechanical seal leakage that cannot be modeled accurately as functions within the Reynolds equation. Some of these factors include:

- Shaft misalignment
- Machine vibration
- Seal face or gasket damage

- Unknown fluid properties
- Thermal environment

However, some broad statements can be made about what to expect from certain seal designs in some general applications and some guidelines can be given about leakage behavior.

Conventional Liquid Lubricated Seals

These seal designs comprise a massive majority of the global seal population. By "conventional" is meant flat seal faces with no surface treatment or active lift technology such as lube-grooves, waves, scallops, or other pattern. Conventional liquid lubricated seals can be categorized into five general service types:

Low Duty Applications

These applications are defined by the following parameters, all of which must be satisfied:

- Shaft rotation $\leq$ 3600 rev/min
- Sealed pressure $\leq$ 22 bar (319 psi)
- $-40°C \leq$ Sealed temperature $\leq$ 180°C ($40° \leq T \leq 356°F$)
- Shaft diameter $\leq$ 100 mm (3.937 in)

Seals in these services should produce very low or even nonvisible leakage. Leakage should be measured in drops per hour or mL/hr.

Phase Change Applications

These are services in which the sealed fluid changes from liquid to vapor at some radius within the sealing interface. The change in specific volume during a phase change from liquid to vapor is dramatic. Fluids such as methane and propane expand by a factor of 240 times, and carbon dioxide and ammonia expand by factors of 600 and 800 times, respectively. Seals designed for these services will have net closing forces sufficient to overcome this expansion, but leakage will be in vapor form.

The accepted method for measuring leakage of light hydrocarbons, refrigerants, and other chemicals that flash to vapor within the sealing interface involves measuring the concentration of the chemical in some volume surrounding the machine. Usual units of measure are parts-per-million (ppm) or even parts-per-billion (ppb) in some cases. Many legal limits on seal leakage are stated in these units as shall be discussed later. If one can imagine 225 FIFA regulation soccer balls submerged in an olympic-size swimming pool, this corresponds to a concentration of 500 ppm. (An olympic-size pool is 50 m × 25 m × 2 m [164 ft × 82 ft × 7 ft], and a FIFA regulation soccer ball is 21.96 cm [8.65 in diameter]).

This "leakage" measurement is unique because it is not a leakage metric at all. Leakage is a mass or volume flow with respect to time. A ppm measurement is only a concentration. The value *will* be a function of seal leakage, but also wind velocity, enclosure geometry, and other nearby emission sources. EPA Method 21 used in the United States addresses and makes allowance for these issues and does identify seals that are producing emissions, but it is difficult to correlate measured values to any seal design analytical software.

High Duty Applications

These applications are defined as those that exceed one of the limits described above. Examples of these services include:

- Multistage centrifugal pumps in utility boiler feedwater service, where pressure, temperature, and speed can be quite high and fluid viscosity very low.
- Mining autoclave agitator seals, where temperature and pressure are high and shaft movement can be erratic as solids strike the impeller blades.
- Pulp and paper refiners and pressure grinders, where shaft movement can be extreme, and the fluid stream is full of fibrous material.
- Crude oil, liquefied natural gas (LNG), and multiphase pipeline pumps, where sealed pressure is very high, vapor pressure margin might be very low, and fluid stream properties change significantly as different crude and LNG streams are pumped from the well.

Seals in these critical services normally produce leakage measured in units of drops per minute (dpm), with 1 to 2 dpm being normal and even 10 dpm normal in some services.

Transient Services

Start-stop operation or fluctuating operating conditions will result in leakage rate swings. Transient leak rates can be as high as 100 times steady-state, and in some cases may be only partially reversible. The underlying mechanics of transient sealing is beyond the scope of this work, and a proper treatment of the subject would extend into complex behavior requiring advanced numerical techniques. For an interesting approach to ring-on-ring transient wear (Wang, et al., 2004; Messé and Lubrecht, 2002; Salant and Cao, 2005). Some broad statements can be made:

1. Mechanical changes in seal faces (pressure, stress) occur via elastic waves that travel at sonic speeds, whereas thermal changes propagate much more slowly.

2. Rotordynamic effects in rotating shafts during transient load or speed conditions are extremely hard to predict.

Statement 1 relates to how the terms h, $\partial p/\partial r$, and μ interact. The ∂p term can change at whatever rate that variable is changed. This could be as slowly as a pressure regulator adjusted gently by a human operator or as rapidly as a pump impeller increases pressure as it is accelerated by a motor start. Changes in viscosity, μ, are not as tightly coupled. Viscosity could decrease as the sliding velocity of the seal faces increases and generates heat. Viscosity could also increase if the sealed pressure ∂p is reduced and less heat is generated. Viscosity could simply change as the process fluid is heated or cooled. In any case viscosity changes will always lag the driver of the change. And remember the film thickness, h, is a cubic contributor to leakage and also a strong function of viscosity during dynamic operation! So during unsteady thermal and mechanical conditions there are several competing variables, many of which are functions of one another. The actual value of seal leakage, m, at any given instant is really anybody's guess.

Statement 2 is not governed by the Reynolds equation per se, but rather renders its underlying assumptions invalid. Shaft bending or orbit, for example, causes misalignment of the seal faces to one another that can result in unusual face wear or gasket damage. Vibration in the axial direction can separate the seal faces well beyond the natural Reynolds film thickness, h, and then drive the faces into contact as the rotating face oscillates back and forth. Additionally, the seal gaskets may not be able to track this motion properly, causing leak paths. Vibration in the radial plane can accelerate face wear or even pump fluid across the seal faces in a manner not related to the Reynolds equation mechanics.

Slurry Services

Contamination of the fluid *film* with solid matter will increase the leak rate by scratching or chipping the sealing surfaces, but this is not the typical way slurry fluids cause leakage. More frequently, solids will gather at the dynamic gasket and prevent it from functioning properly. Other slurries do not "de-water" as they are centrifuged in the sealing chamber, if the percent solids (by volume) is high and the solids are not significantly denser than the carrying liquid. This often results in dry running and thermal destruction of the seal faces since the solids laden fluid cannot enter the seal face gap. These macroscale misbehaviors render leakage impossible to predict. If the slurry does de-water and measures have been taken to minimize gasket fouling, the leakage statements from paragraph 1 will apply.

Engineered Liquid-Lubricated Seals

For the purpose of this paper, "engineered" liquid lubricated seals are defined as those that have some sort of surface treatment or pattern on one of the seal faces that either aids lubrication or prevents contact altogether by means of hydrostatic or hydrodynamic lift. This would include hydro-grooves, waves, spiral grooves, scallops, or nontraditional surfaces such as matte lapped, hydropores, diamond-like coatings, or the like. Most seal manufacturers have proprietary software that can predict leakage as a function of several parameters, and many of these designs are dynamically tested by the manufacturer before shipment.

Noncontacting Gas Seals for Pumps

Seals of this design are applied in centrifugal pumps operating between 1460 and 3600 rev/min with shaft diameters between 25 and 125 mm (.98 and 4.92 inch) in diameter. (Usually dual gas seals are installed in centrifugal pumps designed to the ASME B73.1 and DIN EN 733 or 22858.) Aerodynamic lift generated by some seal face pattern or surface creates a gas film thick enough so that zero face contact occurs. Seal manufacturers will provide typical leakage curves as a function of seal size and/or shaft speed so that the end-user knows what to expect. Refer to Figure 1 for a general footprint for leakage.

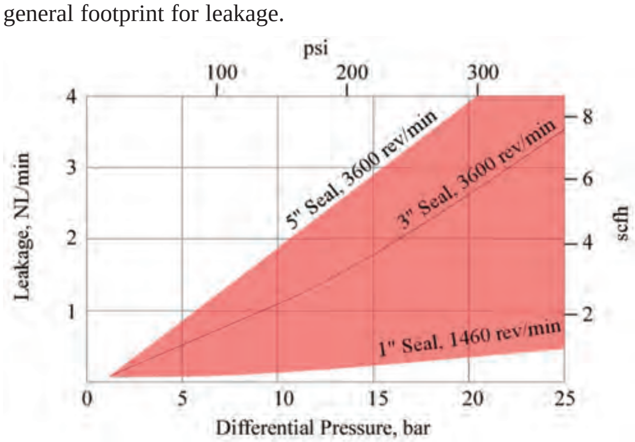

Figure 1. Leakage for Noncontacting Gas Seals.

It can be difficult to interpret barrier gas consumption values in the field. Most control panels use variable-area flowmeters ("rotameters") that require the visual reading to be multiplied by a correction factor in order to obtain a value for flow at standard temperature and pressure (STP) conditions. Most commercially available flowmeters have visual scales calibrated for STP, which is 20°C (68°F) and 1 atm. However, the gas flowing through the flowmeter is at barrier pressure and can be at a different temperature. The following formula can be used.

$$NL/\min_{true} = NL/\min_{visual}\sqrt{\frac{313\cdot(P_B+1.0)}{SG\cdot(T_B+273)}}(SI)$$
$$SCFH_{true} = SCFH_{visual}\sqrt{\frac{530\cdot(P_B+14.7)}{SG\cdot 14.7\cdot(T_B+460)}}(USCust) \quad \textbf{(4)}$$

where:
P_B = Barrier gas pressure, psiG or barG
T_B = Barrier gas temperature, °F or °C
SG = Gas specific gravity (1.0 for air, 1.02 for nitrogen)

Figure 1 is a typical leakage map that shows how leakage is a function of both seal size and speed. Many gas seals in service exhibit leakage well below the values in this map, but seal engineers focus more on the leakage *signature* than the actual reported value. A leakage signature can be defined as a data plot of leakage rate versus time and any other process variable such as pressure, temperature, or shaft speed. Of course one needs to be below normal expected limits, but if the pump is operating at steady-state then leakage should be steady as well. The flowrate should not bounce around randomly, toggle between two values, or trend upwards or downwards with respect to time. Such fluctuations are often indicative of intermittent face contact or dynamic gasket misbehavior, usually with a dramatic failure looming in the near future. For example, a very steady leakage rate of 2.0 NL/min is much more desirable than a leakage rate that fluctuates between 0.1 and 1.0 NL/min in chaotic fashion.

Split Seals for Pumps

Leakage from split seals is a controversial subject. The split seal market is very competitive and ripe with innovation. At least 50 U.S. patents have been awarded since 1980 in the field of split mechanical seals. Innovations notwithstanding, few seal manufacturers publish expected leakage values since the assembly and installation of these seals have the biggest influence on performance. The practitioner is urged to measure split seal leakage in units of drops per minute rather than mass or volume flowrate. This implies that sealing of hazardous chemicals should not be attempted with split seals.

Each seal manufacturer has anecdotal knowledge of zero-leakage split seal applications, but these are typically the exception rather than the rule. Most split seal installations leak 10 to 15 dpm under static pressure, then after dynamic operation of 24 hours or so decrease to 2 to 7 dpm. Of course these are rather average expectations, which will vary up or down based on the following:

- Seal size—larger seals leak more
- Sealed pressure—higher pressures create more leakage
- Pump health and construction—vibration, misalignment, or corroded surfaces will only cause higher leakage
- Seal face combination—carbon graphite versus silicon carbide or alumina oxide (ceramic) will leak less than silicon carbide versus itself
- Skill of the seal installer
- Accessibility of the seal chamber for installation

Dry-Running Mixer/Agitator Seals

Typical bottom and side entering mixers tend to behave like low speed pump seals in the section above, *"Conventional Liquid Lubricated Seals."* However on top entering mixers, dry running, contacting seals can be used due to the low speed and pressures at which many of these machines operate. Typical seal arrangements include:

- Single seals, sealing the vapor space above the vessel contents, which may be at a positive or negative pressure.
- Dual-pressurized seals, sealing instrument air, nitrogen gas, or steam as a barrier fluid.

Leakage for these designs behaves much like a gas orifice, which reaches choked flow conditions at which point increased pressure differential across the seal face only yields a nominal increase in mass flow. This is due to the much thinner fluid film compared to an active-lift gas seal. The film thickness will be equal to the combined surface roughness of the seal faces. Practically speaking, at some point operation will be governed not by leakage but rather the pressure*velocity (P-V) limit of the seal face materials in contact. Most seal manufacturers publish commercial P-V limits, and results of P-V tests of different material combinations is available in the public domain. A P-V limit is typically expressed in units of psi-ft/min or bar-m/s. The pressure term, P, usually refers to the contact pressure acting on the wear area of the narrower seal face, but other sources use the sealed differential pressure for the P term. The V term can be reported as the sliding velocity of the mean face diameter or the balance diameter. Some seal manufacturers present P-V limits as a family of curves. Often one will find P-V limits that are practical limits of face distortion due to pressure or heat generation, not the tribological interplay of the face materials, per se. One must also understand what each published P-V limit is based on. The limit could be one at which a one-year or three-year seal life at steady-state conditions can be expected, for example. Be sure to inquire.

Noncontacting Gas Seals for Mixers/Agitators

These seal designs are usually dual-pressurized arrangements sealing instrument air or nitrogen gas at a pressure higher than the vessel pressure. Although the designs are similar to dual gas seals for pumps, the active lift must rely solely on hydrostatics because the shaft speeds are too low to rely on aerodynamic lift. The hydrostatic lift design requires a minimum pressure differential across both face sets, typically at least 3 bar (44 psi). This results in leakage that is greater than that of pump gas seals.

Compare the difference in the shape of the leakage curve family in Figure 3 to Figure 2. For the dry-running, contacting seal, the film thickness is equal to the combined surface roughness of the two seal faces in contact, and that does not change with increased pressure differential. So choked flow conditions are reached at some pressure as previously discussed. For noncontacting seals, the film thickness increases as pressure differential increases, so choked flow is difficult to obtain. Leakage is typically a second order function of differential pressure for any given shaft size.

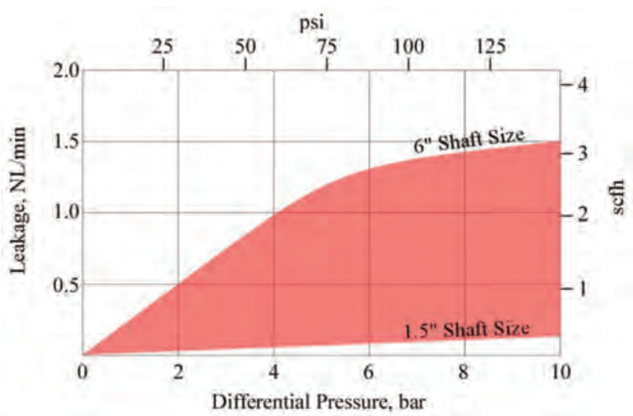

Figure 2. Dry-Running Gas Seal Leakage for Mixers.

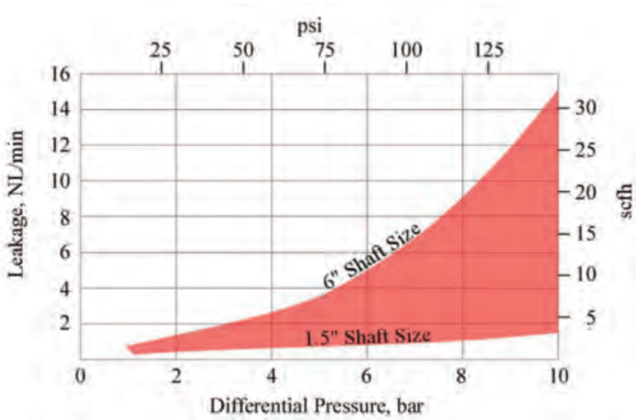

Figure 3. Noncontacting Gas Seal Leakage for Mixers.

Split Seals for Mixers/Agitators

Split seals are often applied in low duty, top-entry mixers where speeds and sealed pressures are very low. In many applications a mechanical seal is installed to keep atmospheric air or contaminants out of the vessel more so than containing the vessel contents. Seal leakage, regardless of direction, should not be an issue in these instances or a split seal is a poor choice.

These designs are quite often dry-running as discussed in the section above, *"Dry-Running Mixer/Agitator Seals."* With atmospheric air above and vessel vapor space below, there is little alternative. Whether dry-running or liquid lubricated, the seal manufacturer is really the only one that can make statements regarding leakage, and do not expect much detail. If this is a problem for the end user, revisit whether a split seal is a good selection.

Noncontacting Gas Seals for Compressors

Self-acting gas seals designed for compressors and turbomachinery can be applied at pressures over 400 bar (5800 psi) and speeds in excess of 200 m/s (656 ft/s). Modern compressor seals are manufactured to much tighter tolerances and fits than other seal designs and undergo rigorous testing prior to shipment. These designs require seal face features that create aerodynamic lift in order to prevent any face contact whatsoever.

But the Reynolds equation still governs leakage. The high sliding velocities combined with the aerodynamic lift features create film thicknesses on the order of 2 to 5 μm (79 to 197 μin), and most process gases have dynamic viscosities on the order of 1e-06 kg/m-s (0.001 cP). This explains the higher leakage values expected from compressor seals as shown in Figure 4. Note that the vertical axis is in U.S. units of scfm rather than scfh.

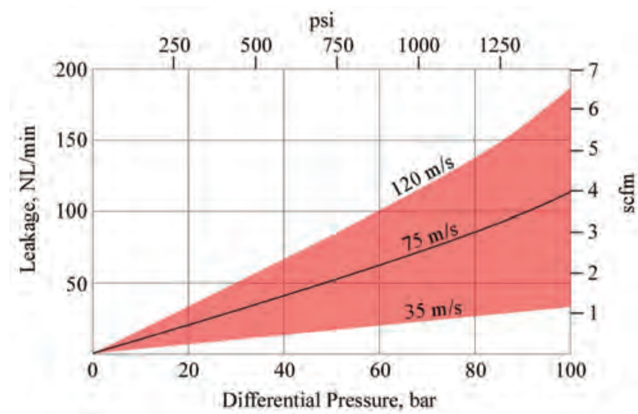

Figure 4. Dry-Running Gas Seal Leakage for Compressors.

CATEGORIES OF LEAKAGE LIMITS

Leakage Limited by Law

Increased health, safety, and environmental (HSE) awareness has spawned comprehensive federal and state/provincial legislation in nearly all industrialized nations. Those nations that are still developing their industrial infrastructures have rapidly evolving HSE legislation. Such legislation usually targets certain chemical compounds that the scientific community has determined to be acutely detrimental to living organisms and the environment. A basic approach limits human exposure to a listed chemical in terms of parts-per-million over some specified time period. More advanced legislation is designed to protect the environment by specifying emission limits of types of chemicals by a single source or site. The most advanced laws reach beneath the site level and govern emissions of individual components such as pumps and valves.

One could write a several-volume treatise on environmental regulations that apply to industrial sites and equipment used at those sites, and even those volumes would need to be updated frequently as laws change. The purpose of this section is to give the reader a starting point for researching what applies to his or her site of interest as well as which chemicals are commonly found in environmental legislation.

A list of environmental governmental agencies and legislation for the major industrialized nations is included in Table 1. Many countries with advanced health, safety and environmental legislation limit the release of specific chemicals to the environment. Those references can be found in Table 1 as well. Only federal laws are listed. Many provinces, states, or special geographic areas have more detailed local regulations as well. Most of the members of the European Union have federal enforcement agencies and overlapping federal environmental legislation.

Table 1. Environmental Agencies and Regulations in Several Industrialized Nations.

Nation	Agency	Federal Regulation
Argentina	Federal Council on the Environment (COFEMA)	The General Statute of the Environment (25.675 General del Ambiente), 2002
Australia	Department of the Environment, Water, Heritage and the Arts, National Environment Protection Council	National Environment Protection (Air Toxics) Measure, 2004, *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act)
Brazil	National Council for the Environment (CONAMA)	National Environmental Policy (PNMA), enabled by Federal Law 6938 on August 31, 1981
Canada	Minister of the Environment	Canadian Environmental Protection Act (CEPA), 1999
China	State Environmental Protection Administration (SEPA)	Environmental Protection Law of the People's Republic of China, 1989
Egypt	Egyptian Environmental Affairs Agency (EEAA)	Law Number 4 of 1994
European Union	European Environment Agency	EU Directives 84/360/EEC and 96/61/EC (IPPC)
India	Central Pollution Control Board	National Air Quality Monitoring Programme (NAMP) and Proposed Effluent and Emission Standards for Petroleum Oil Refineries
Indonesia	Office of the State Minister of the Environment and Badan Pengendalian Dampak Lingkungan (BAPEDAL)	Act No. 23 of 1997 concerning the Management of the Living Environment (the 1997 Environmental Management Act).
Japan	Ministry of the Environment	Air Pollution Control Law
Malaysia	Department of the Environment	Environmental Quality Act, 1974
Mexico	Secretaría de Medio Ambiente, y de Recursos Naturales (Semarnat)	Ley General del Equilibrio Ecológico y la Protección al Ambiente, 1998, Articles 110-116
New Zealand	Ministry for the Environment	National Environmental Standards for Air Quality, 2004
The Philippines	Department of Environment and Natural Resources	Philippine Clean Air Act of 1999
Russian Federation	Ministry of Natural Resources	The Regulations On The Ministry of Natural Resources of the Russian Federation, Resolution # 370, 2004
Saudi Arabia	Presidency of Meteorology and Environment	General Environmental Regulation, Council of Ministers Resolution No 193, 2001, the Environmental Protection Standards (General Standards) Document No 1409-01 1982, Royal Commission in Respect of the Industrial Cities of Jubail and Yanbu, 1999
Singapore	National Environmental Agency	Environmental Pollution Control Act, 2001 (See the Schedule Standards of Concentration of Air Impurities at the end of the act.)
South Korea	Ministry of Environment	VOC: Regulated Substances and Dischargers, 2006
Taiwan	Environmental Protection Administration	Stationary Pollution Source Air Pollutant Emissions Standards, 1992
Thailand	Pollution Control Department	The Enhancement and Conservation of the National Environmental Quality Act B.E. 2535 (NEQA 1992)
United Arab Emirates	Federal Environmental Agency	Federal Law No 24 of 1999
United States	Environmental Protection Agency (EPA) and Occupational Safety and Health Administration (OSHA)	40 CFR 63, National Emission Standards for Hazardous Air Pollutants for Source Categories, and 29 CFR 1910.119, Process Safety Management of Highly Hazardous Chemicals
Vietnam	Ministry of Science, Technology and Environment	1993 Law on Environmental Protection

Typically, a governmental authority will work with an environmental team at any given customer site. The environmental team then advises the different maintenance or operation areas regarding units or machines that are out of compliance. Those crews then work with the seal vendors to remedy the situation. So seal manufacturers do provide different solutions in different geographic areas but it is at the direction of the end user's area supervisor, not the governmental agency directly. It is important for multisite end users to understand why the same seal company might be recommending different solutions (single seal, dual seal, different barrier fluid) for the same or similar applications worldwide. Rarely will the seal vendor "know the law" but will have an experience set that has developed under the local law.

Leakage Limited by Process

In this context shall be discussed the leakage of a barrier fluid from a dual seal arrangement into the process fluid. Also considered will be the ingress of carbon wear debris and other contaminants from a single seal into the process fluid. Leakage can be categorized into the process fluid into three sections: liquid leakage, gas leakage, and material leakage.

Liquid Leakage

Dual pressurized seals that use a liquid as the barrier fluid force a very small amount of leakage into the process fluid. The leakage rate is typically low because the pressure differential across the innermost seal faces is low (review the Reynolds equation…$\partial p/\partial r$…). Even so, this issue must be discussed with the end user even before suggesting use of a dual pressurized liquid seal. Several issues can arise:

- *Chemical or thermodynamic problems*—The end user's engineering group can offer advice on what barrier liquids could cause or prevent an unwanted or desired reaction, respectively.
- *Process fluid dilution*—Many applications, primarily involving mixer seals, must be very pure to be commercially competitive or acceptable within quality limits. Common examples include standard pharmaceuticals, specialty chemicals, beverages, religious law governed foods, or other chemicals meant for human or animal consumption.
- *Process fluid aesthetics*—Process fluids such as cosmetics, beverages, creams, textiles, and paints must meet very demanding color or viscosity requirements to meet quality standards.

Gas Leakage

Leakage of instrument air, steam, or nitrogen gas can create some unique challenges for the process stream or machine itself. Instrument air and steam are rarely used as barrier gases. Air contains oxygen, which cannot enter many mixing vessels or reactors for fear of jeopardizing the stoichiometric balance or initiating combustion. Steam has certain advantages in biopharmaceutical applications since it tends to kill bacteria or other organisms, but is rarely used elsewhere. Finding elastomers that are compatible with steam can also be quite an adventure. That leaves us with nitrogen gas, a cheap and inert substance with well-known properties.

Two major effects must be considered before using a dual gas seal on a pump or mixer:

- *Gas entrainment in centrifugal pumps*—Leakage of barrier gas into a centrifugal pump will be centrifuged to the eye of the impeller during operation. Whether this will cause a noticeable decrease in total dynamic head production depends on what volume the gas occupies at the impeller eye relative to the flow through the pump and the impeller design. Low-flow, high-head pumps are at serious risk. Gas leakage can also accumulate while the pump is dormant but the barrier pressure is maintained. This can pose a risk to any pump if the gas accumulation is high enough (Turley, et al., 2000; Gabriel and Buck, 2007a).
- *Loss of Δp in mixer seals*—As discussed previously, slow speed gas seals require a minimum pressure differential in order to avoid face contact. This is because low speed seals must rely solely on hydrostatic lift. While many reactor vessels are pressure-controlled by some device, some are not. Barrier gas leaks across the inboard seal faces and adds molecules to the vapor space in the vessel. If not pressure controlled, the vapor space pressure will increase as leakage continues. Assuming the barrier gas pressure is held constant, the pressure differential (Δp) across the inboard seal can decrease until contact of the seal faces cannot be prevented.

Material Leakage

By "material" is meant such debris as carbon graphite wear particles from a seal face, O-ring lubricant, foreign matter from the seal parts, or other unforeseen contamination. This form of "leakage" is of primary concern to biopharmaceutical and traditional pharmaceutical manufacturers and end users that have very precise aesthetic or ingredient composition requirements.

The quantity of carbon graphite dust that any seal design can generate is typically minute, but process fluids that must be ultra-white (paint, pharmaceutical creams, textiles) may be compromised by even the smallest amount of carbon dust.

Process fluids meant for human or animal consumption must meet the Food and Drug Administration's (FDA) requirements in the U.S. and many other nations. Carbon graphite seal rings comprise carbon, a hydrocarbon, or resin binder, and some impurities such as ash and other trace compounds. Nearly every modern carbon graphite seal material has been found generally regarded as safe (GRAS) by the FDA with the exception of those that use antimony as a binder.

O-ring and gasket lubricants that most end users will permit:

- Dupont Krytox® greases carry a USDA H-2 grade.
- DowCorning® 111 Valve Lubricant and Sealant meets U.S. FDA 21 CFR 175.300 and National Sanitation Foundation Standards 51 and 61.
- Klüberfood NH1 87-703 Hygienic Grease meets the requirements of German food law (LFGB, §5, 1/1), complies with the guidelines of 21 CFR 178.3570 of the FDA, and conforms with NSF H1 requirements.

Leakage Limited by Housekeeping

Seal leakage to atmosphere can be in solid, liquid, gas, or multi-phase form. Leakage can also change phase if allowed to freeze, melt, precipitate, or evaporate. "How much leakage is too much" can be determined by a four-tier analysis:

Hazard to Personnel

These include:

- Bodily harm due to fires, explosions, or toxic substance releases initiated by seal leaks.
- Slip hazards due to liquid leakage or condensed steam quench.
- Slip hazards due to frozen leakage or condensation.
- Eye and skin hazards due to leaking vapors or spraying liquids.
- Burn hazards due to hot leakage. A surface or liquid above 50°C (122°F) provides a contact exposure limit of eight minutes before second degree burns are probable, and third degree burns can be expected in ten minutes. Hot water at 68°C (154°F) can cause a third-degree burn in one second.

Hazard to Equipment

In all seal installations there will be devices and structures such as electric motors, bearing frames, gearboxes, shaft couplings, baseplates, scaffolding, support pedestals, or fasteners. Leakage from a failed mechanical seal ("spray") can find its way through labyrinth seals and into bearing frames and electric motors, causing significant damage. Drip leakage can corrode fasteners and structures not designed to come into contact with the process, barrier, or quench fluids and compromise their integrity or create sharp or abrasive surfaces.

Odor Limits

Personnel exposure limits notwithstanding, most conscientious workers do not want to work in a facility that stinks. Contractors, consultants, and neighbors share this opinion. 3M™ Occupational Health and Environmental Safety Division publishes a *Respirator Selection Guide*, which lists odor thresholds for many chemical compounds in units of parts per million. The CHRIS Manual (Chemical Hazards Response Information System) is published by the U.S. Department of Transportation and lists similar odor threshold data.

Facility Aesthetics

General cleanliness standards vary widely from plant to plant and across different industries. This issue should be addressed before proposing new seals and support systems as well as continually throughout their life.

Leakage Limited by Support System

Normal seal leakage rarely outpaces the capabilities of modern seal support systems, but off-design or damage-mode leakage may need to be considered during the proposal stage or when establishing planned maintenance (PM) schedules. A logical way to examine systems is by piping plan, as designated in API 682/ISO 21049 (2006). Of course not every piping plan needs to be discussed.

API Plan 23 (Figure 5) uses a heat exchanger to cool a recirculated volume of process fluid through the seal chamber. This plan is used extensively in hot water applications in the power industry and light hydrocarbon applications in petroleum refining.

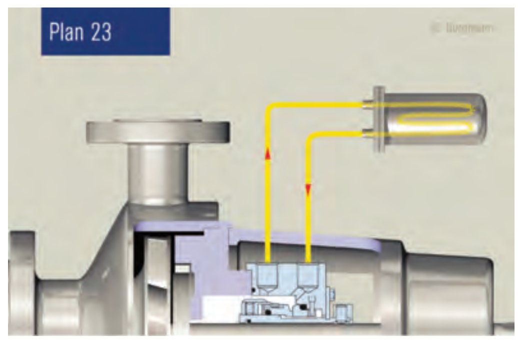

Figure 5. API Plan 23.

The effectiveness and energy efficiency of the Plan 23 cannot be overstated, but face seal leakage for whatever reason can undermine performance in an autocatalytic manner. The mass of fluid that leaves the recirculating loop via the seal must be replaced by new fluid from the pumping stream. This fluid entering the recirculated Plan 23 loop will be at the much higher process temperature. As this hotter fluid mixes into the recirculated stream it will cause an increase in loop temperatures. This temperature increase will decrease the viscosity of the fluid and also raise the vapor pressure. Both of these effects are usually undesirable and can lead to face damage and higher leakage, and thus even higher loop temperatures. This effect can be simulated by cracking the vent valve on the Plan 23 system and allowing recirculated fluid to exit.

Normal face seal leakage from a properly applied conventional seal design will not trigger this path to failure, so no analytical work prior to commissioning is required here. But the end user must be aware of this potential scenario and understand its physical meaning. As a proactive measure, collected leakage (if possible) can be compared to loop temperature readings to see if a downward performance trend is initiating. Those circumstances where leakage cannot be "collected" include vaporization and evaporation. A vaporizing hydrocarbon can be sniffed for a ppm level, and those levels compared to loop temperatures. If the leakage evaporates (like water) before it can be measured then the leakage rate is not high enough to draw a significant amount of hot process fluid into the loop.

API Plan 52 (Figure 6) systems use an unpressurized reservoir filled with a buffer fluid to capture process fluid leakage past the primary seal face of a dual seal arrangement. The process fluid must then be vented or drained from the reservoir, depending on whether it is in liquid, vapor, or both phases. Abnormally high primary seal leakage in the form of vapor can create backpressure in the reservoir. Abnormally high primary seal leakage in the form of liquid can displace the buffer fluid from the reservoir and damage the secondary mechanical seal or cause a process fluid emission to atmosphere. Buffer fluid leakage past the secondary mechanical seal can drain the reservoir and cause the secondary mechanical seal to run dry and fail.

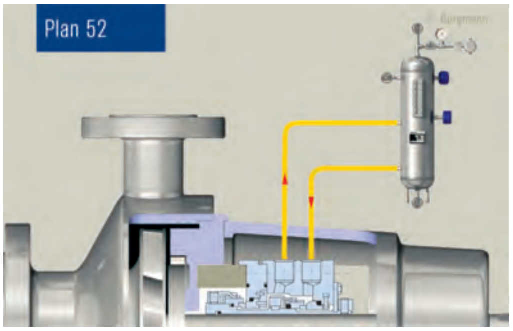

Figure 6. API Plan 52.

API Plan 53A (Figure 7) systems rely on a pressurized vapor space above the barrier liquid in the reservoir. If the dual seal leaks through either the inboard, outboard, or both seals, the barrier liquid level decreases. Figure 8 shows how the normal liquid level in a typical reservoir can drop below the low-level alarm switch, then below the visible part of the level gauge, then below the return line level, and even below the supply line level so that the seal can eventually run dry.

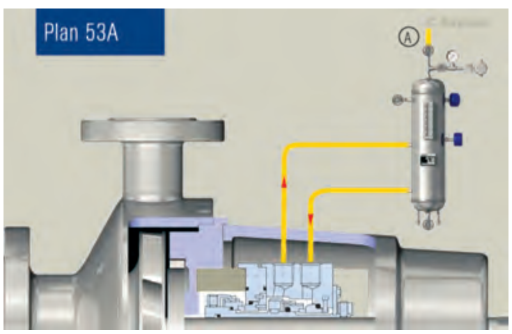

Figure 7. API Plan 53A.

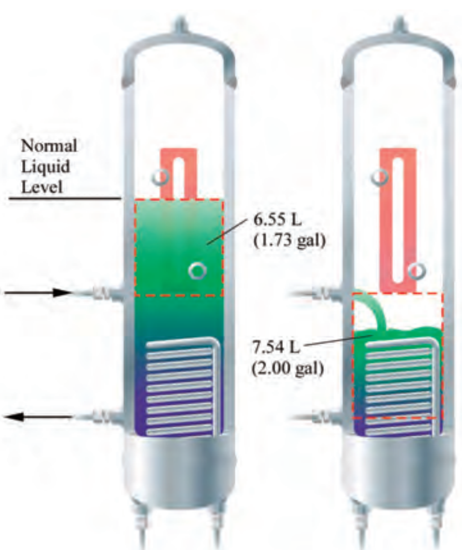

Figure 8. Typical Plan 53A Reservoir.

Plan 53A systems are found in all industries. Three to 20 liter (one to five gallon), uninstrumented tanks are deemed acceptable in some markets while 80 liter (20 gallon) reservoirs with complex digital instruments are used in critical refinery applications. All seal manufacturers can assist the end user on how to properly design these systems in terms of reliability and expense.

Plan 53B systems have no vapor-to-liquid contact, which eliminates the possibility of gas dissolving into the barrier liquid at higher pressures and causing secondary seal face damage. Barrier pressure is maintained by a precharged gas bladder that increases the barrier pressure as liquid is forced into the accumulator (usually via a hand pump) and reduces the volume of the bladder (Figure 9). The bladder does not shrink in volume nearly that much in reality. Most accumulator manufacturers suggest precharging the gas bladder to 80 percent of the desired system pressure, and that usually inflates the bladder close to filling the entire inner volume of the cylinder. Via the ideal gas law, the bladder will decrease in size by about 20 percent. One can see that the volume, v_1, of *barrier fluid* in the accumulator cylinder is actually quite small, given that most accumulators range from one to five gallons (3.8 to 18.5 liters).

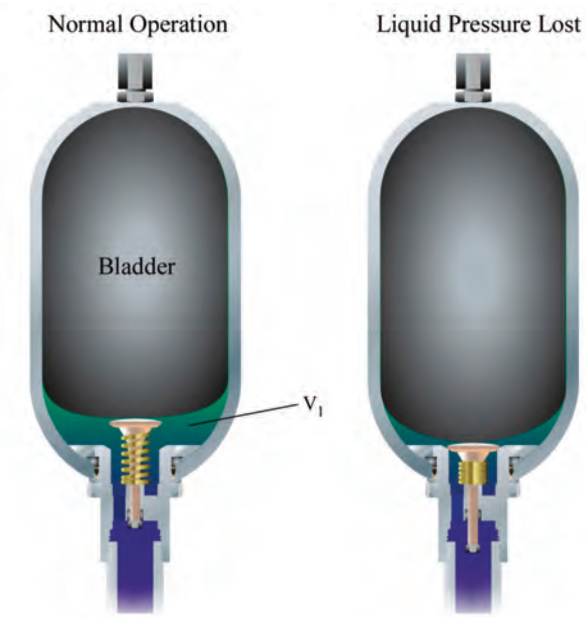

Figure 9. Plan 53B Accumulator.

Most routinely inspected locations allow leakage make-up with a hand pump mounted next to the system. Some very large accumulators are used in remote locations such as pipeline pumping stations and offshore oil drilling platforms. Larger accumulators offer a slower pressure decay for a given leakage rate simply because v_1 is larger. Other end users combine the use of large accumulators with barrier pressures that are *much* higher than the process pressure, thinking this allows for more pressure decay before a pressure reversal could occur. This is valid, but one must also consider the higher seal face leakage and heat generation that will accompany the higher barrier pressure. Seal face generated heat is typically linear with respect to sealed pressure, and leakage is also theoretically linear with respect to $\partial p/\partial r$ as revealed by the Reynolds equation. Both generated heat and leakage can be modeled to determine the ideal barrier pressure but any barrier pressure greater than 7 bar (102 psi) above process pressure must be *carefully monitored* during the first few months of operation before written operating procedures are finalized.

API Plan 53C (Figure 10) arrangements are used in applications where the barrier pressure must maintain a constant *multiple* of a process pressure that varies for some reason (Figure 11). These arrangements are common on dual-inline designs, where barrier pressure forms an internal diameter (ID) pressure differential on the primary mechanical seal faces. ID pressurization results in tensile stresses that seal face materials can only support at moderate levels. The Plan 53C maintains a constant, lower ID pressure *differential* when the process pressure changes. Common multiples are 1.10, 1.12, and 1.15. Seal leakage will allow the piston to rise as barrier-side volume in the transmitter decreases. Once the piston becomes pinned, the multiple suddenly drops to 1.0, meaning barrier pressure equals process pressure. After that barrier pressure will drop below process pressure.

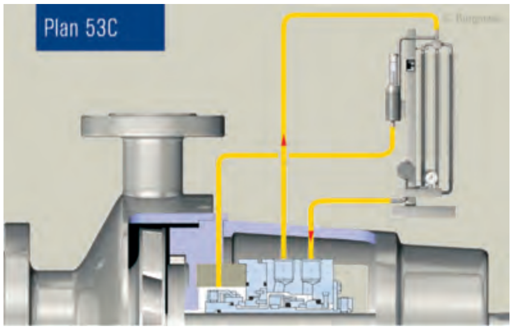

Figure 10. API Plan 53C.

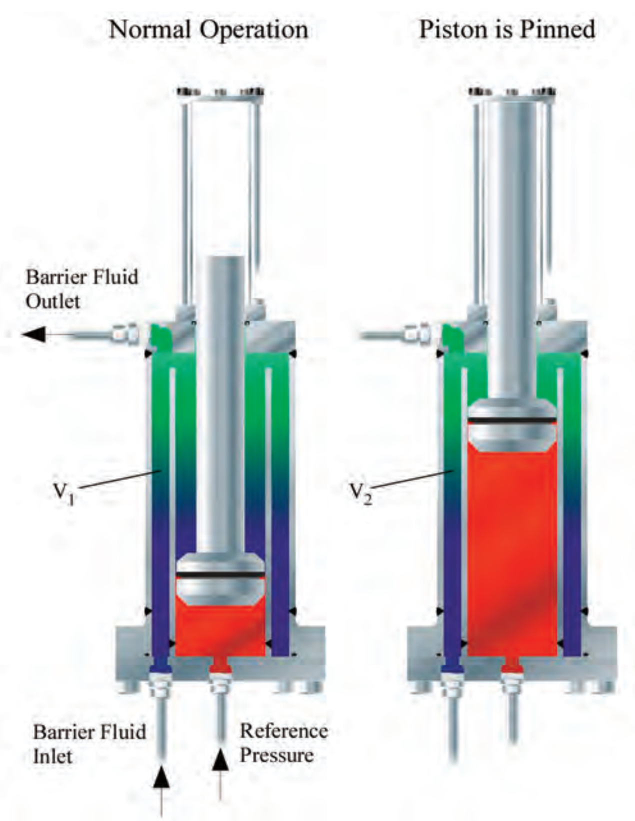

Figure 11. API Plan 53C Transmitter.

For this reason Plan 53C systems are often accompanied by a refill hand pump as described in the Plan 53B system. The seal manufacturer can advise an end-user how to schedule refill based on the transmitter volume, v_1. Most transmitter designs also have clearly marked high and low barrier volume gauges. (Be very aware of process or barrier fluid thermal expansion when using pressure transmitters.)

Some seal users use one pressure unit to support several dual pressurized seals. For an array of noncritical, low duty seals this may be efficient but in any other case is ill advised. A fault or failure of the pressure unit can cause the entire seal array to fail. A single seal failure may cause enough drop in barrier pressure or flow to fail other seals in the array (Gabriel and Buck, 2007b). Allowable seal leakage of any one seal or combination of seals will be governed by the hydraulic characteristics of the pressure unit.

Leakage Limited by Standard

API 682/ISO 21049 (2006) sets objectives and minimum performance requirements for qualification testing. Section 10.3.1.4.1 states the permitted leakage rate shall be less than:

- 1000 ml/m^3 (ppm vol) concentration of hydrocarbon vapors using EPA Method 21;
- An average liquid leakage rate less than 5.6 grams/hr per pair of sealing faces.

INTERPRETING LEAKAGE DATA

Mechanical seal users measure and report seal leakage in many ways. The sophistication of measurement typically correlates to the consequences of leakage or component failure. On one extreme, leakage of cooling tower water pumps might be captured in a crude plastic container every day or so and reported in units of “1 to 2 liters per day.” At the other extreme, barrier gas leakage into a highly toxic phosgene pump may be electronically recorded every second by expensive instruments that can govern the shutdown of expensive production machines.

The following serves as a crude algorithm for interpreting mechanical seal leakage data:

- *Start-up leakage of a new seal*—If the leakage value is more than two orders of magnitude (factor of 100:1) than what is expected, the seal is very likely damaged or improperly installed. Removal and inspection are warranted. If leakage is between one and two orders of magnitude than what is expected, carefully measure the leakage trend. If leakage is constant for 48 hours, remove the seal and inspect. If leakage is downward trending, then continue to run the seal until steady-state leakage is obtained and review that value with the manufacturer.
- *Upward trending leakage of a mature seal*—This usually is the result of gradual damage to the seal faces in the form of chipping, scratching or radial taper. If the machine runs at steady-state conditions and the leakage is upward trending and linear the seal can remain in service until some agreed upon value.
- *Chaotic leakage ranging across one or more orders of magnitude, machine is at steady-state*—This is the hardest data to interpret. In fact, an interpretation should probably not be attempted. If this is a critical service then the seal should be removed and inspected either immediately or at the next logical opportunity depending on the situation. Possible causes for this behavior are outside the scope of this work.
- *Increase in leakage that corresponds to a change in vibration signature*—If the increase in leakage is less than an order of magnitude, it may correct itself over time. If increase in leakage is more than an order of magnitude it is likely the result of irreversible or autocatalytic damage.

CONCLUSIONS

This paper is meant to give the end user a structured approach to dealing with mechanical seal leakage. That approach can be summarized as follows:

- Develop a basic understanding of the theoretical formula for leakage and the variables of which leakage is a function.
- Understand the expected leakage values (hopefully provided by the seal manufacturer) for the seal type at issue.
- Be aware of the environmental regulations that govern your site or area.

- Be aware of the effects of seal leakage on your process stream.
- Address the health and housekeeping issues with appropriate engineering controls, seal selection, or work instructions.
- Thoroughly train personnel on the function of the seal support system and how it behaves.
- Measure, record, and diagnose seal leakage intelligently with the help of your seal supplier.

As the focus in industry shifts from capital expense to total life cycle cost, this approach to seal technology will be quite important. End users will be faced with more complex decisions about which seal design to purchase based on many of the issues raised in this paper.

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