MAGNETIC FLUID FEEDTHROUGH PRIMER

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INTRODUCTION

Magnetic fluid feedthroughs are vital components in many modern vacuum systems. They are also used in other process systems. Yet, for many users, a certain mystery has surrounded these devices. This primer seeks to clarify any mystery by describing the technical foundations on which these feedthroughs stand.

Several factors should be considered when selecting the most appropriate feedthrough for a given application. This primer provides an overview of these technical issues. In many cases, this information will be sufficient to make a good choice.

These products have been used in many complex applications. Rigaku engineers are ready to help customers find the most appropriate feedthrough for a given application. In some cases, a custom design may be needed.

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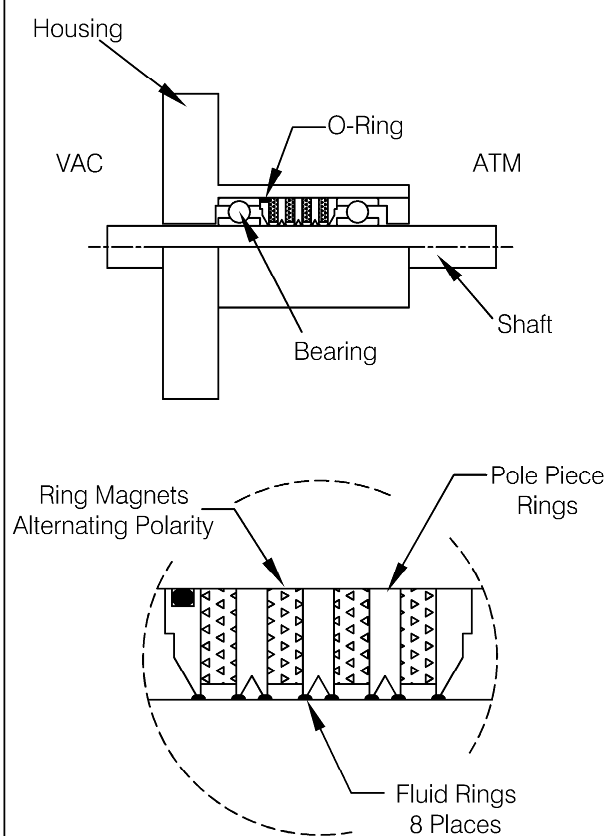
Basic Sealing Principle

Dynamic sealing is accomplished by a hermetic liquid seal that permits free rotation of the shaft. Several different arrangements of housing, shaft, bearings, magnets and fluid have been used over the years. Figure 1 illustrates the patented design employed in Rigaku's RMS family of products. Other designs will be discussed in later sections.

Magnetic fluids are stable colloids comprising a base liquid, ferromagnetic particles, and a dispersing agent that suspends the particles in the base liquid. The ferromagnetic particles interact directly with an external magnetic field. Because of the strong coupling to the magnetic particles via the dispersing agent, the base liquid interacts indirectly with the magnetic field. Hence magnetic fluids can be pushed, pulled, and shaped by magnetic fields. In feedthroughs, narrow rings of fluid (shown here in red) form liquid barriers filling the annular spaces (or gaps) between a rotating shaft and the tips of a stationary pole piece. Radially, the fluid rings are bounded by the shaft and the pole piece tips. Axially, the rings are free surfaces at gas-liquid interfaces, restrained only by magnetic forces. Magnetic flux density at the pole tips is very large. Hence, any axial displacement of a liquid ring away from the pole tip results in a force that resists the displacement. The isolated volumes between adjacent rings are important in the functioning of the device.

FIGURE 1



Maximum sustainable pressure difference across a single liquid ring is less than 1 atmosphere. Consequently, practical devices require a series of separate rings with small, isolated gas volumes between each pair of rings. The total pressure difference (typically 1 atmosphere in vacuum applications) is divided over several stages.

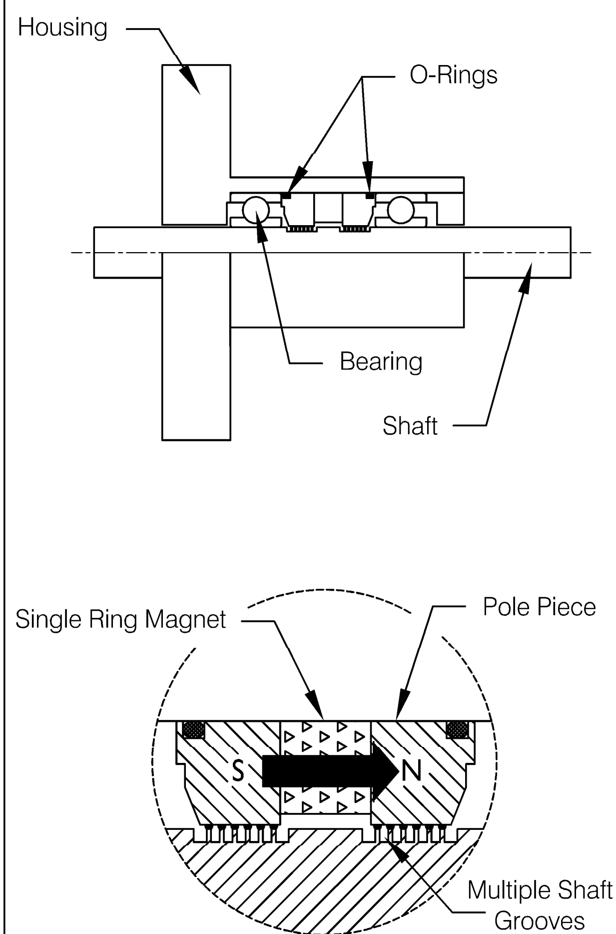
Dimensions and locations of shaft and pole tips are critically important for reliable operation. A complete system of shaft, pole piece, bearings, housing, and other parts provides the necessary precision in a single package that is easily integrated into a vacuum system. Note that a single O-ring provides static sealing between the pole piece and housing.

DESIGN IMPROVEMENTS PIONEERED BY RIGAKU

Figure 2 shows how the earliest commercial products used a single ring magnet in combination with two smooth-walled pole pieces and a shaft that contained multiple grooves. This type of design is still used by some manufacturers (but **NOT** by Rigaku), despite the fact that it has several significant drawbacks:

- The grooves weaken the shaft in two ways. First, the shaft diameter at the bottom of the grooves is reduced. Second, the corners of the grooves act as stress concentration points. In shafts of small diameter, the reduction in shaft strength is quite substantial.
- Because this early design uses only a single magnet, the entire device has a significant overall magnetic polarity. In some applications the external magnetic field can be a serious problem. At a minimum, it is an annoyance.
- The two separate pole pieces require each one to have its own O-ring seal to the housing. A leaky vacuum-end O-ring will escape detection by an ordinary helium leak test, since the other O-ring will not allow helium to pass. In such a case, the feedthrough would contain a large virtual leak (the region between the two O-rings, including the magnet) and would also have reduced pressure capacity since the inner fluid sealing stages would be bypassed by the virtual leak region.

FIGURE 2



By comparison, the patented Rigaku design of Figure 1 has these advantages:

- Full shaft diameter is maintained throughout the magnetic sealing region, for full strength.
- Four ring magnets (two pairs) are arranged with alternately opposed polarity. One magnet of each pair opposes and substantially nulls out the external field of its partner. So the entire feedthrough has only a very small residual external field.
- At the same time, the opposed-pair arrangement results in exceptionally high fields in the sealing region, thereby maximizing the force holding the sealing fluid in place against the external pressure gradient.
- Because the magnets and pole rings are constructed as an integral pole piece unit, only one O-ring static seal to the housing is required. This O-ring is located at the vacuum end of the pole piece. Helium passes freely to the O-ring and all around the pole piece during leak testing. No virtual leak can exist because there is no trapped internal region.

"SUPERSEAL" - A BREAKTHROUGH IN FEEDTHROUGH DESIGN

Researchers at Rigaku have found a way to simplify and further improve the design of fluid sealed feedthroughs. Figure 3 illustrates the **SUPERSEAL** concept.

Two opposed-polarity magnets are placed within the rotating shaft and the housing (made of ferromagnetic material) is an integral part of the magnetic circuit. A number of carefully formed grooves on the surface of the shaft determine the location of the fluid sealing rings. Because the shaft diameter is larger than the bearing journals in the region containing the magnets and grooves, there is no loss of strength as a result of using a grooved shaft.

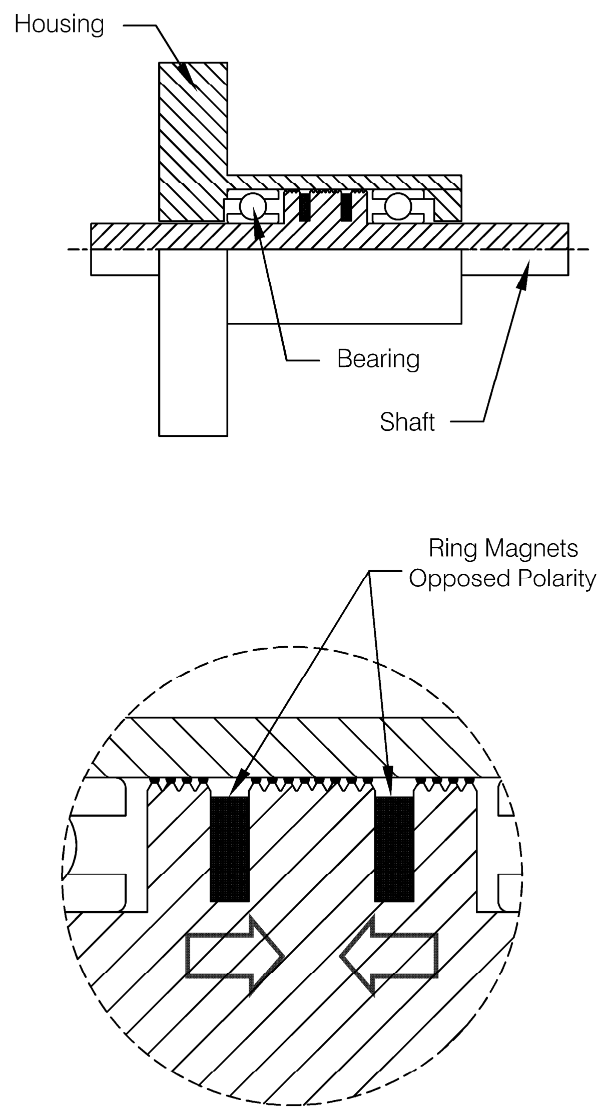
The magnets are embedded in a matrix of ferromagnetic shaft material, which acts as a magnetic shunt. The casual observer may think this would weaken the magnetic field in the fluid seal region, leading to a very weak seal. However, the reality is that by proper selection of materials and careful design, it is possible to make **SUPERSEAL** feedthroughs with very high pressure capacity.

Benefits of the **SUPERSEAL** design are:

- Requires fewer parts
- Provides better alignment between seal components
- Permits extremely low external magnetic field because housing is magnetic
- Uses no internal static seal (O-ring), thereby eliminating a potential source of leakage

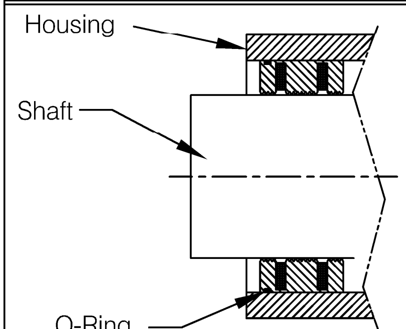
The **SUPERSEAL** design is protected by United States and International patents.

FIGURE 3



In some applications, it is desirable to use a separate pole piece. Here a related design, called **SUPERSEAL II**, can be used. Figure 4 shows a pole piece machined from a single piece of magnetic stainless steel, with small internal grooves to define the fluid regions. The shaft is smooth. Magnets are mounted in deep internal grooves. This design minimizes the number of parts required to produce a separate pole piece. Because the housing is not part of the magnetic circuit, an O-ring is required for static sealing of pole piece to housing.

FIGURE 4



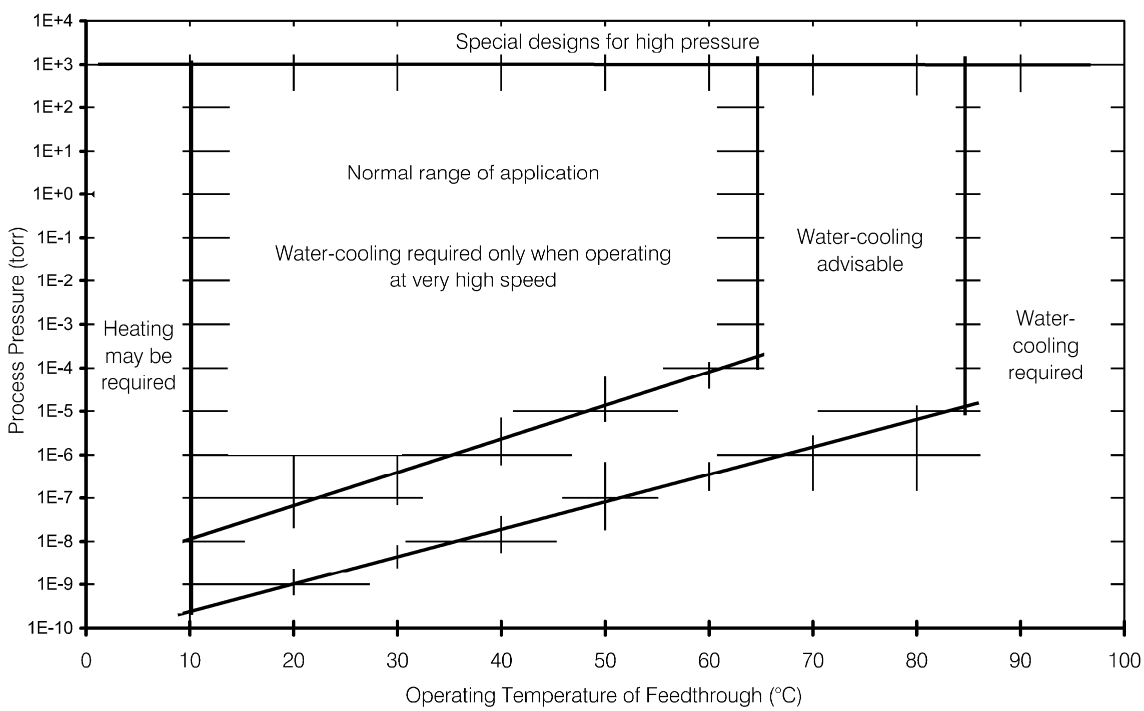
APPLICATION FACTORS

Magnetic fluid feedthroughs are appropriate for many applications, but it is important to consider two groups of application factors when selecting a specific model for a particular application. ***Environmental factors*** always include process operating pressure and ambient temperature, and may include other process-related factors as well. ***Mechanical factors*** include speed, loads (radial and thrust), duty cycle, and bearing ratings.

ENVIRONMENTAL FACTORS

Figure 5 shows some broad operating guidelines for process pressure and feedthrough temperature. Water cooling (or heating) extends the useful temperature range. Units can be designed for use at high pressure.

FIGURE 5



Temperature limits are based on the properties of magnetic fluids and other construction materials. Although rarely encountered, low temperatures can increase fluid viscosity sufficiently to require unacceptably large driving torque. High temperatures cause deleterious chemical and physical changes in fluids and other materials.

Pressure limits are determined by magnetic design and fluid properties. The lower limit is set by the vapor pressure of the base liquid (temperature dependent) in combination with the process tolerance for fluid vapors. Higher pressure ratings can be achieved by adding more stages. Standard products offer maximum pressure capacity of as much as 2.4 atmospheres (2.4 kg/cm^2).

In cases of high-speed operation, the self-heating of the viscous magnetic fluid becomes a significant cause of elevated temperature. Surface speeds up to 7 m/sec are possible without water cooling *(DN* = diameter × rpm = 120,000 mm-rpm). With water cooling, surface speed can be increased to about three times this value.

MECHANICAL FACTORS

Except for light-duty applications, mechanical operating factors have great impact on the performance and lifetime of feedthroughs. Wholly apart from vacuum considerations, bearings and shafts must support each application's requirements for speed, load, duty cycle, torque transmission, end play, and so on. Thorough consideration of these factors is beyond the scope of this discussion, but a few key points can be mentioned here.

Shaft sizes must be large enough to transmit the required torque from motor to load over the full range of anticipated acceleration and speed. Possibilities of jamming should be taken into account.

Bearings must be rated to handle the radial and axial loads to be experienced in service. Significant tradeoffs exist between radial load, axial load, operating speed, duty cycle, operating temperature, lubrication, and bearing lifetime. Thus, any "load rating" of a feedthrough as a single number cannot be an adequate characterization over a realistic range of applications. Users should be aware that bearing lifetime varies strongly with load and speed, according to the following equation:

$$L_{l0} = \frac{A(C/P)^3}{N} \qquad (1)$$

where L_{l0} = bearing life expectancy (90% confidence)
A = lubrication factor (normally less than 1)
N = operating speed, RPM
C = "dynamic load rating" of the bearing (depends on bearing size)
P = "dynamic equivalent load" (combination ot radial and axial loads)

Thc main point to note from this equation is that bearing life varies linearly with rpm and exponentially *(as the third power!)* with load and rating. Loading the bearings beyond their rating leads to *very* rapid failure.

As a practical matter, selection of appropriate models can often be guided by previous experience in similar applications. Rigaku should be consulted for recommendations and application assistance in selecting feedthroughs for unusual applications.

IMPACT OF FEEDTHROUGH ON PROCESS

Feedthroughs can make undesirable secondary contributions to the vacuum process environment because of the presence of magnetic fluids, bearings, and magnetic fields. Users should consider whether any of these contributions might be significant in a particular application.

Magnetic fluids are the most mysterious of these elements for most users; their properties are discussed more fully in a later section. With respect to their possible impact on the process environment, the main considerations are vapor pressure and chemical composition. Each feedthrough contains a small free surface of fluid iu contact with the vacuum space. The area of this surface is approximately given by the relationship:

$$A \sim 0.3 * D \quad (2)$$

where A = area of free surface, mm2
D = shaft diameter, mm

Fluid evaporates from this free surface at a rate proportional to vapor pressure (1E- l0 to 1E-12 torr at 20°C for typical fluids). Not much can be done to reduce the area of the free surface, but it is possible to select fluids with the lowest vapor pressures. However, fluids with the lowest vapor pressure typically have very high viscosity, leading to an increased torque requirement to operate thc fccdthrough. At high speeds, this leads to increased self-heating, raising the local temperature (and the vapor pressure) of the fluid. The most common fluids are based on hydrocarbons with vapor pressure in the neighborhood of 1E-10 torr (20° C). Fluids based on perfluorinated polyether (PFPE) materials can also be obtained (vapor pressure approximately 1E-12 torr).

Bearings can contribute particles to the process because most feedthroughs employ a "straddle" design in which one ball bearing is placed on each side of the magnetic seal system. The vacuum-side bearing generates particles that depend on load, speed, and lubrication. Grease lubricants with low vapor pressure (PFPE matcrials) arc commonly used. When exceptionally low particulate generation is required, dry-lubricated bearings can be specified, but load-carrying capacity is substantially reduced and cost is increased. In some cases (e.g., very high speeds) ceramic bearings may be justified (very expensive). Sometimes a "cantilever" bearing arrangement is employed in which both bearings are located on the atmosphere side of the seal. This isolates the bearings and lubricants from the process, but also increases the size and cost of the feedthrough.

IMPACT OF PROCESS ON FEEDTHROUGH

Most operating environments (except where high temperatures are present) are benign, with no adverse impact on these devices. It is important to be aware of the unusual cases in which the environment threatens thc feedthrough, especially as a result of foreign matter finding its way into the bearings or the fluid region. Four such cases are discussed here.

Reactive process gases wreak havoc with hydrocarbon-based magnetic fluids, causing the feedthrough to leak. In some cases, reactive gases also lead to gummy deposits on bearings, causing mechanical failure. Cantilever bearing arrangements (both bearings on the atmosphere side of the seal) protect the bearings, but not the sealing fluid.

Particulate matter generated by the process can find its way into the seal region. Small amounts of this can become jammed into the narrow magnetic gap between the shaft and pole piece, causing the shaft to vibrate as it rotates. Labyrinth or lip seals are sometimes used to reduce the ingress of material. Lip seals used in this way necessarily result in small, isolated volumes located between the lip seal and the fluid seals. In some processes, the resulting virtual leaks can be tolerated.

Solvents used during cleaning of the system can destabilize the colloid system of the magnetic fluid, leading to instantaneous major leakage. Cleaning solvents must be used with care, limiting the quantities employed in the neighborhood of the feedthrough. When the feedthrough is located at the bottom of the system, with vertical shaft orientation, the chances of flooding are greatly increased.

Solvents sprayed on the atmosphere end of the feedthrough while hunting for gross leaks have damaged many feedthroughs. This leak-testing technique must not be used on feedthroughs.

MATERIALS CONSIDERATIONS

Most applications arc well served by feedthroughs of standard design. However, users should be aware of the materials used in constructing feedthroughs to be sure they are compatible with the system environment in which the feedthrough will operate. Table 1 lists the materials commonly employed in these feedthroughs. Rigaku can provide more specific information.

TABLE I

MATERIALS USED IN FEEDTHROUGHS

Material	Where Used	Comments
Stainless steel, nonmagnetic	Housing, flange	303 and 304
Stainless steel, magnetic	Shaft, pole piece, Superseal housing	17-4PH (SUS 630) and 416
Bearing steels	Balls, rings	SAE 52100 (SUJ 2)
	Retainers (ball cages)	Usually pressed from carbon strip steel. Stainless steel available on special order.
Magnet alloys	Magnets	Magnets are normally isolated from the vacuum space by some of the fluid rings, so are not usually an issue with respect to process compatibility. Rigaku uses SmCo and NdFeB. Other manufacturers often use AlNiCo.
Elastomers	Static O-ring seals	Viton© O-rings provide static vacuum sealing between housing and pole piece.
Hydrocarbons, fluorocarbons	Magnetic fluids	Formulations are proprietary. Major constituent is the base oil, which is typically alkylnaphthalene, or PFPE in Rigaku feedthroughs. See Table 2.
Adhesives	Epoxies and thread-locking compounds	Epoxies, if used, are normally isolated from the vacuum space by some of the fluid rings, so are not usually an issue with respect to process compatibility. If threaded retainers are present on the vacuum face, it is possible that some locking compounds have been used. Consult manufacturer for details in such cases.

Typical characteristics of magnetic fluids are summarized in Table 2. Since these fluids are proprietary materials, this table must be understood as a very broad characterization.

For many applications, hydrocarbon-based fluids are entirely satisfactory. PFPE fluids offer lower vapor pressures, but present significantly higher drag. It is important to ensure that motors and drive systems can handle the starting and running torque of the feedthrough.

TABLE 2

TYPICAL MAGNETIC FLUID MATERIAL PROPERTIES

	Hydrocarbon	Fluorocarbon	
Vapor pressure, torr at 20º C at 100º C	 6E-10 2E-5	 2E-11 5E-7	Fluorocarbon fluids (Krytox© , Fomblin©) have lower vapor pressure
Viscosity, centipoise at 20º C	300	5,000	Hydrocarbon fluids have lower viscosity, lower drag
Magnetization, gauss	450	200	Hydrocarbon fluids are “magnetically stronger”, can provide higher pressure capacity with fewer sealing stages. However, Superseal technology minimizes the practical effect of this difference.

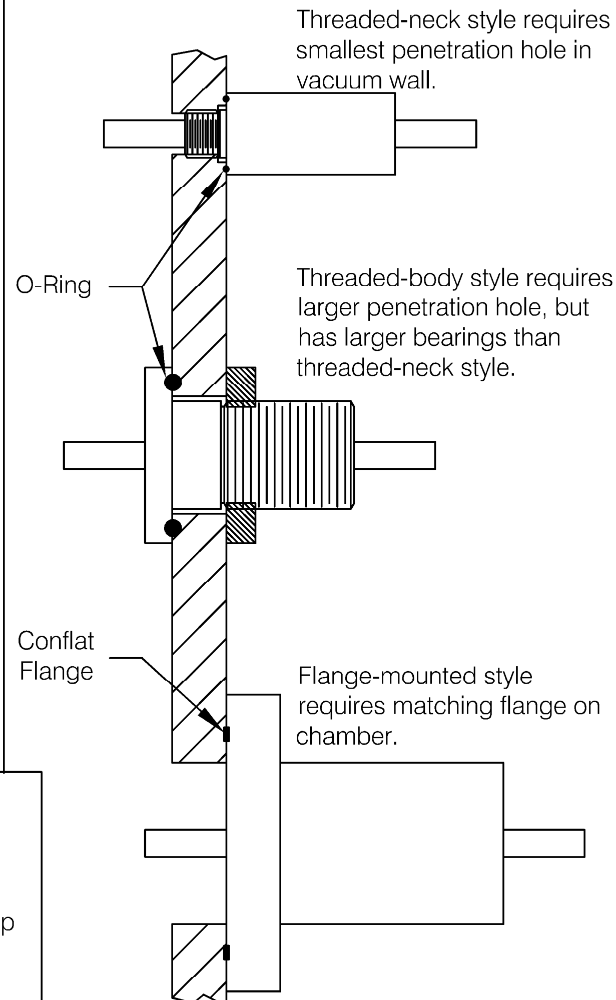
Application Examples

Light-Duty Feedthroughs

Examples of this category include shutters for evaporation and sputtering deposition sources, positioning systems for multi-pocket E-beam evaporation sources, sample positioners, and chopper wheels. Shaft diameters are typically 6 mm to 10 mm. Figure 6 illustrates three mounting styles for popular products with 6.35-mm shaft diameter.

FIGURE 6

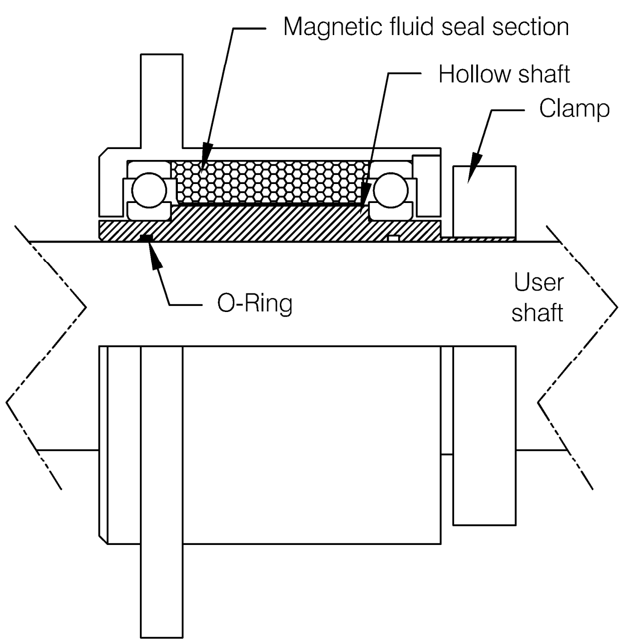
Light-Duty Feedthroughs, 6.35 mm Shaft Diameter



Hollow Shaft Seals

In applications where shafts are large, complex, proprietary, or subject to design revision, hollow-shaft feedthroughs can often be used to advantage. Hollow-shaft feedthroughs provide a complete bearing and seal package in which the shaft is a tube or sleeve with closely controlled inside diameter. Thc user joins this package to the shaft to form a complete assembly suitable for the application. A static O-ring seal between the hollow shaft I.D. and the user shaft O.D. is required. Some positive means of driving the hollow shaft via the user shaft is required to ensure that the user shaft does not move relative to the hollow shaft, an event that would damage the static O-ring seal. Figure 7 illustrates the typical case.

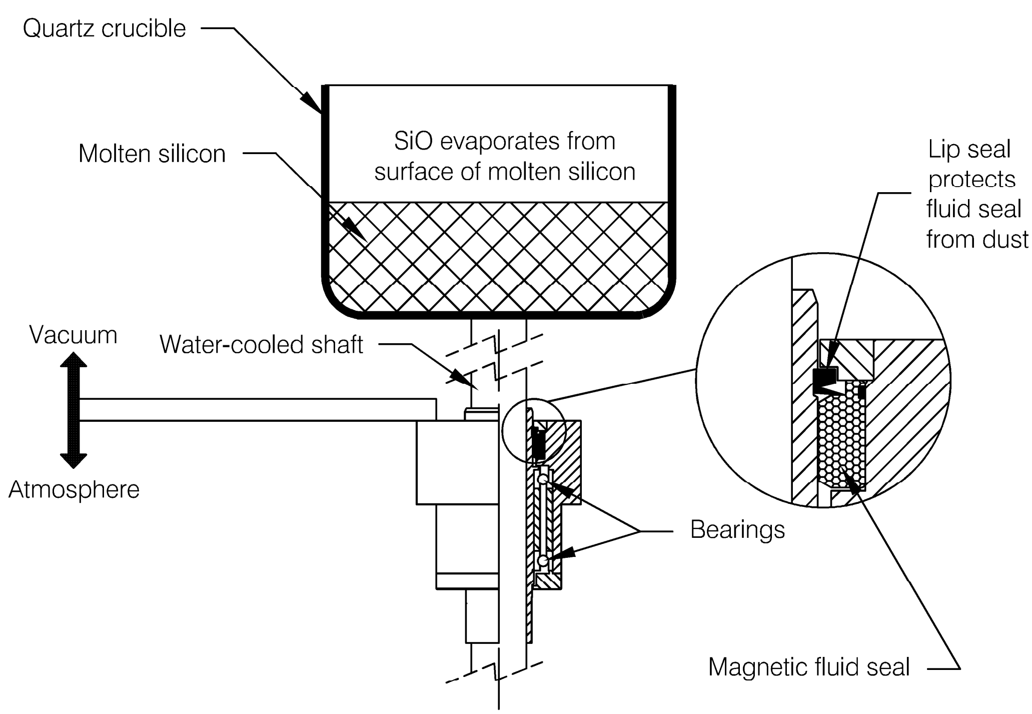
FIGURE 7



CRUCIBLE ROTATION SEAL FOR CZOCHRALSKI SILICON CRYSTAL PULLER

Figure 8 shows how a magnetic fluid feedthrough is used in a process that generates a great deal of finely divided dust (SiO) that would rapidly degrade bearings and seal. A cantilever bearing design separates bearings and process, and a lip seal isolates the magnetic fluid seal from the process, increasing the number of process cycles that can be run before the seal must be serviced. During the crystal growth process, the operating pressure is maintained at about 20 torr by flowing argon through the process vessel. This is well above the high-vacuum range. However, the process is very sensitive to oxygen and nitrogen, so sealing must be of the same high quality as in high-vacuum systems. This is a custom-designed product.

FIGURE 8



Coaxial Feedthrough for Robotic Arm

Robotic arms are widely used to handle silicon wafers and fiat-panel displays in cluster tools and other semiconductor processing equipment. Two independent motions are required. One method of achieving this is to nest one feedthrough inside another, as illustrated in Figure 9.

The outer shaft is supported in the housing by bearings near the bottom and top ends. The outer fluid seal is outside the vacuum space, making this a cantilevered design.

The inner shaft is supported within the outer shaft by another set of bearings. In the case shown here, the inner shaft bearings are in the straddle configuration, with the upper bearing in the vacuum space.

Products of this degree of complexity are always custom-designed. Rigaku engineers must work closely with the customer's design team on this kind of project.

FIGURE 9