Moving systems of indicating instruments must be supported to allow the desired degree of rotation with a limited amount of friction and eccentricity between fixed and moving parts. The most widely used means for supporting any type of instrument moving system, be it a moving coil, iron vane, or moving magnet, is that of a jewel and conical-pivot or cylindrical-shaft construction. The shaft or conical pivots are usually rigidly attached to the moving system and rotate between two jewel bearings. Such construction is also being increasingly applied in miniaturized devices of many sorts. This article will describe differences of application of the two most common types of instrument jewel bearing systems and will discuss the design considerations of each.

Types Of Bearing Systems: The two types of bearings to which this discussion will be limited are the vee-jewel and the ringstone, Fig. 1.

Vee-jewels are used extensively in electric indicating instruments in which bearing friction torque must be kept to an absolute minimum in order that instrument accuracy will always be within specified limits. For true indication of the quantity that is being measured, the restoring torque on the moving system must either equal the electrical torque or differ from it by a constant amount. Since friction is not a constant quantity, the bearing friction must be held to a relatively low value for satisfactory instrument calibration. Commercial instruments utilizing the vee-jewel are small panel, switchboard, hook-on, portable and laboratory types, and exposure meters, some of which are shown in Fig. 2. Fig. 3 shows two typical moving systems supported by vee-jewels.

Vee-Jewel Design: If the weight of a moving system operating with the shaft vertical were supported by a theoretically sharp point, the contact area between pivot and jewel would be zero and therefore friction would be zero. An instrument such as this would be very short-lived, however, because shocks and vibration which it would experience in normal operation would soon flatten or distort the points. This would produce friction much greater than would have occurred had the pivot points been slightly rounded originally. For optimum design of the jewel and pivot contour, then, the two major requirements of minimum friction and maximum resistance to deformation must be balanced against each other.

In many applications of electric indicating instruments using the vee-jewel system, the instrument can be operated in any position—with the shaft vertical, horizontal, or in any intermediate position. It can be shown analytically that the maximum friction error exists when the shaft is horizontal. For this reason the remainder of the
discussion of vee-jewels will deal with horizontal friction only. In this position, as the moving system is actuated, friction causes the pivots to roll up the jewel wall until the wall becomes too steep to support rolling, and slipping occurs. This action is illustrated in Fig. 4a. The maximum friction torque resulting at this point is

\[ T = \mu W R_p \cos \theta \]  

(1)

where

- \( R_p \) = Pivot radius, millimeters
- \( T \) = Maximum horizontal friction torque, gram-millimeters
- \( W \) = Weight of moving system
- \( \mu \) = Coefficient of static friction between jewel and pivot
- \( \theta \) = Angle of pivot roll from neutral position to point on jewel at which slipping occurs, degrees

A more accurate expression for friction torque in a horizontal axis system has been derived by Nylander.\(^1\) It involves another important design consideration—end-play of the moving system. The equation is

\[ T = \mu W R_p \cos \tan^{-1} \left( \frac{\mu}{P_r} \right) \cos \sin^{-1} \left( 1 - \frac{P_r}{P_r - R_\mu} \right) \]  

(2)

where

- \( P_r \) = End play with the pivot contacting the spherical surface of the jewel, millimeters
- \( R_j \) = Jewel radius, millimeters

Equation 2 is shown graphically in Fig. 5 which, for particular values of R21, W, and R1, shows how end-play affects friction torque. Two interesting observations can be made from this graph:

1. At end-plays of 0.001-inch and greater and a coefficient of friction of 0.10 or less, the friction torque is practically independent of jewel radius.

2. With the end-play reduced below 0.001-inch, an appreciable decrease in friction torque can be attained even with a relatively large coefficient of friction.

However, Figs. 4b, 4c, and 6 illustrate that the normal force at the contact area between jewel and pivot increases rapidly as end-play is decreased below 0.001-inch. It is seen, then, that minimum end-play cannot be the only criterion in reducing friction because high wedging forces accompany small end-play. If this wedging force is not kept within certain limits, serious pivot deformation can occur resulting in increased friction. A series of experiments conducted by Stott2 showed that for an included pivot cone angle above 30 degrees the maximum allowable stress increases with cone angle. In addition, the rate of increase of bearing pressure with decrease in pivot radius depends upon the weight of moving system, Fig. 7.
Equations 1 and 2 indicate that for a given bearing system the friction torque varies linearly with moving system weight, provided, of course, the bearing surfaces are clean and polished so that does not vary with load. In most cases, the rolling angle \( \phi \) is small and Equation 1 reduces to

\[ T = \mu W R_p \]  

In the design of an instrument using a vee-jewel and pivot system, the coefficient of friction \( \mu \) and moving system weight \( W \) known, the maximum
allowable friction torque is usually known, (it depends primarily on the instrument sensitivity) and the pivot radius can be calculated. The jewel radius is made a maximum consistent with holding the eccentricity of the moving system within allowable limits and the contact stress within the elastic limits of the materials used.

**Shock-Resistant Jewel Mountings:** In certain instrument applications shock forces sometimes produce stresses in the jewel and pivot which would exceed the maximum allowable stresses if the jewel were mounted rigidly. The most common method for protecting the bearing system against such forces is that of mounting the jewel on a helical spring. Th the majority of applications, this construction is perfectly satisfactory. For conditions of extreme shock and vibration, however, a recent development using sponge rubber has been proved superior because of its damping characteristics. As an example, one small panel instrument design, to meet an extremely stringent military specification, must withstand severe amplitudes and frequencies of vibration, tumbling in a steel barrel, and nine shock blows ranging from 1200 to 2000 ft-lb. The acceleration present when such shocks are applied is in the order of 1000\(g\).

The basic design approach was essentially that of protecting the most vulnerable part of the instrument, the moving system. This was accomplished by cushioning each jewel with a small piece of sponge rubber.

The internal portion of the jewel screw is so designed that shock forces applied in any direction will move the jewel away from the pivot, Fig. 8. The jewel moves due to its own inertia rather than from armature acceleration force directed through the pivot. When the shock force is along the axis of the pivot, the jewel moves as a result of the blow. The pivot is restrained to a travel of 0.010-inch by a shoulder on the pivot support. The action of the soft sponge rubber is to damp the jewel motion severely, thereby preventing it from rebounding onto the pivot. Shock forces applied perpendicular to the axis tend to tip the jewels, allowing the pivot to strike the jewel on the periphery of its cone rather than the tip. The armature is restrained to a travel of 0.010-inch in this direction also.

**Ringstone and Endstone Bearing Systems:** A moving system using ringstone jewel bearings has higher friction torque than a comparable vee-jewel system because of the larger contact surface between pivot and jewel. Some types of electric instruments can tolerate higher friction torque, however. Ringstones can therefore be used to advantage in producing much more sturdy bearing systems. For the same weight of moving system, the one supported by ringstones has a much lower bearing pressure than the vee-jewel.

Ringstones are used in preference to vee-jewels under the following conditions:

1. When bearing friction is negligible compared with the active electrical torque or with other friction or error-producing torques. An example is a recording instrument in which the moving system drives a pen across a chart. Here, the friction of pen on paper far exceeds the friction present in the bear-
ings.
2. When the instrument in normal operation is subjected to continuous vibration, thereby reducing bearing friction torque. Aircraft instruments mounted on an airplane panel are an example of this application.
3. When the mechanical construction requires that the shaft extend through the bearing.
4. When side-play of the moving system must be extremely small.

There are various types and combinations of ringstone systems, as illustrated in Fig. 9. In instruments such as recorders where the shaft is always vertical, Fig. 9a, a ringstone-endstone combination is used for the bottom bearing, while the top bearing can be either a ringstone or vee-jewel. Fig. 9b shows horizontal shaft ringstone bearing systems. Certain applications require lower friction than can be obtained by the straight-hole ring-jewel. The olive-hole stone and the "bombe" type are refinements which give lower friction by virtue of the smaller pivot to jewel contact area. The bombe type is used in very special applications where minimum thrust as well as journal-bearing characteristics are required.

It is possible to hold the side-play of a moving system employing ringstones to a lower value than can be obtained with vee-jewels. Fig. 10 shows dimensions of a typical ring jewel. Note that the tolerances are given in ten-thousandths of an inch. The shaft can, of course, be made to the same

**Jewel Materials:** Jewels of various materials, such as glass, sapphire, synthetic spinel, titanium oxide, beryllium copper, brass, etc., have been tried and tested. Depending upon the moving system weight, it has been determined that borosilicate glass and sapphire afford the optimum in initial friction, resistance to impact, and long life.3

In recent years, glass has become a substitute for sapphire in some vee-jewel applications, particularly small panel instruments. As a result of an extensive development program during the war years, when the accessibility of sapphire jewels from Switzerland was uncertain, glass was substituted for sapphire in vee-jewel applications where the total moving system weight is less than 0.75 gram.

The 0.75-gram value for glass vee-jewels has been empirically derived for rigidly mounted jewels and results from an exhaustive series of comparative tests on impact and shock resistance of glass versus sapphire. Of course, this moving system weight limitation can be exceeded if the jewel is shock-mounted.

**Pivot Materials:** The most common pivot material for use with vee-jewels is high carbon tool steel in the form of ground and polished drill rod. After hardening to a minimum Knoop hardness of 690, the pivot tip radius is generally put on by tumbling. Since in ordinary usage the pivot may be subjected to very high tensile, compressive, and impact forces, the microstructure of the hardened pivot is
closely controlled.

Some vee-jewel applications require nonmagnetic pivots to reduce the errors produced by magnetic hysteresis. In such cases monel metal, stainless steel, or tantalum shanks with osmium tips are used, the osmium giving a hardness comparable to the high carbon steel. Pivots of 92 1/2 percent tantalum, 71/2 per cent tungsten are also used for nonmagnetic qualities.

Shafts for use in conjunction with ring jewels are cobalt-tungsten, monel metal, stainless steel, beryllium copper, tantalum, or high carbon steel.

For all pivot applications the material must be highly polished, and free of surface scratches or flaws for minimum friction and longest life.

Summary: Most electric indicating instruments in use today have a jewel-pivot bearing system. In applications where minimum friction consistent with safe loading is the prime factor, vee-jewels and conical pivots are used. When extremely low moving system friction torque can be sacrificed in favor of higher strength or mechanical construction advantage, ringstones are used.

REFERENCES