TEMPERATURE MEASUREMENTS IN FLUID FILM BEARINGS

by

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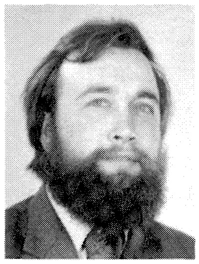

Denis R. Garner joined The Glacier Metal Company in 1969 to work on the fundamental design of all types of hydrodynamic thrust and journal bearings, after receiving degrees in Mechanical Engineering, from the University of Bristol, and Tribology, from the University of Leeds. For eight years, he was responsible for a section providing technical advice on the design and operation of bearings for rotating equipment. Since 1982, Mr. Garner has been responsible for all applications engineering within the Research and Development Organization of the company. This includes research work on bearing operation and design methods, the detailed design of bearings for all types of rotating and reciprocating machinery, and the provision of specialist service such as rotor dynamics and scientific computing.

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INTRODUCTION

Temperature measurements have been widely used in the past to monitor the conditions within hydrodynamic journal and thrust bearings. These temperature readings are appreciably affected by changes in the operating conditions of load, speed, alignment or lubricant supply. If properly installed, the temperature sensors can do more than simply check the condition of the bearing, since they can provide a valuable pointer towards the state of the machine. Since temperatures may be measured relatively easily, such instrumentation provides an extremely convenient detection system for both bearing and machine malfunction.

However, the choice of the location of these sensors has often been rather haphazard, and in recent years various specifications have tried to define preferred positions more exactly. The factors affecting the choice and installation of sensors within bearings are reviewed.

MONITORING TECHNIQUES FOR BEARINGS

Temperature is only one parameter which can be measured to monitor the conditions within a bearing. Operating oil film thickness, oil film pressure and shaft vibration have all been used. The first two of these are very difficult to measure in practice, and give results which are difficult to interpret.

Vibrations measurements, at least those which directly record the shaft to bearing relative displacement (radial or axial), can be extremely useful in monitoring the overall machine condition, but certainly, the precise condition within the bearings can be masked by external machine and foundation influences.

The temperature of the drain oil spilling from the bearing is much easier to record, and traditionally has been used to monitor performance. Unfortunately, the temperature of the oil is not a good parameter to monitor, since it can have poor sensitivity and response to changing conditions within the bearing. The classic example of this is the case of bearing-lining breakup in a plain journal bearing. If this breakup is adjacent to one of the oil feed grooves, then the loss of lining causes an additional flow of lubricant, which is at the supply oil feed temperature, to drain. The recorded drain temperature may even drop, as a direct result of damage occurring with the bearing.

It is far better to record the temperature of the bearing within the active region, where much improved sensitivity and response exists. However, the interpretation of these measurements needs to be given careful consideration. It is seldom adequate to put simple alarm and shutdown limits on a value of temperature dictated by the capacity of the bearing lining material. Most bearings are designed to operate well below any failure temperature, so instead, the instrumentation should be looking for any change in the operational aspects of the oil film. However, the thermal lag within most bearings means that such information cannot be relied upon to provide a safe shutdown under possible conditions of sudden lubrication loss. It can provide alarm and shutdown readings to safeguard against relatively gradual, but potentially dangerous, changes in bearing or machine state (bearing fatigue, machine out-of-balance, or worsening alignment, etc.). The choice of instrumentation type and position is of paramount importance for effectiveness.

TYPE OF TEMPERATURE SENSOR

Temperature sensors are normally of the thermocouple or resistance temperature detector (RTD) type, though occasionally direct reading sensors (i.e., mercury-in-glass thermometers) can be used in larger bearings. The following discussion concentrates on thermocouples and RTDs, since these are the most common forms of temperature sensors used in rotating machinery.

Thermocouple or RTD

The choice of whether to use a thermocouple or RTD is often made by the end user in order to have compatible instrumentation for various requirements in a given plant. This will not necessarily result in the optimum form of temperature sensor for the bearing and, on occasion, may result in difficulties. The plant user may see the sensor readout equipment costs as a major factor in deciding the type of temperature sensor to use. In the past, instrumentation to read RTDs has tended to be cheaper than that for thermocouples, but this difference is now diminishing.

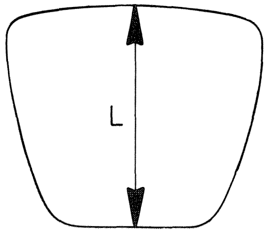
Strictly from the point of view of a bearing designer, thermocouples tend to be preferred, rather than RTDs. This is because industrial RTDs are only available with a minimum diameter of 3.2 mm (0.125 in), whereas thermocouples are available in smaller sizes which are more suitable for fitting to small bearings. The recommended maximum hole size for thrust pads is shown in Figure 1. For pad sizes below approximately 40 mm (1.6 in), RTDs are, in principle, not suitable, if these hole size restrictions are to be observed. If they are not observed, the bearing can be significantly weakened, its load capacity reduced and the temperature reading can be affected. This problem is made even worse when duplex type sensors are specified. If a dual sensor is required, it is better to have two separate sensors in small bearings, rather than one large diameter duplex sensor.

One other disadvantage of an RTD is that some types are not tip sensitive, i.e., the sensing element may measure the average temperature over a significant length, up to about 10 mm (0.4 in). All thermocouples are tip sensitive, by their nature.

Sensor Cable Type

Temperature sensors can be supplied with various types of cable—flexible, rigid or semi-rigid (Figure 2). The choice between these may be governed by installation requirements discussed herein. The semi-rigid type of cable consists essentially of two electrical conductors surrounded by mineral insulation, with a thin stainless steel outer sheath. This type of cable is capable of being bent to an inside radius equal to the sheath diameter, while being sufficiently rigid to require minimal retention. A section through a typical flexible cable, at its simplest, will have the electrical conductors covered with plastic sheathing, but for industrial applications, an additional tough outer sheath (either stainless steel braid or Teflon, or sometimes both) will be used. Lastly, a section through a rigid cable has a thick stainless steel cover over the insulated electrical conductors.

PAD SIZE (L) (mm)	PAD SIZE (L) (in)	HOLE DIA. (mm)	HOLE DIA. (in)
12	0·47	1·3	0·050
14	0·56	1·4	0·055
17	0·67	1·6	0·063
20	0·79	1·9	0·075
24	0·94	2·2	0·087
26	1·03	2·4	0·094
28	1·12	2·6	0·102
31	1·23	2·8	0·110
34	1·34	3·0	0·118
37	1·46	3·2	0·126
40	1·59	3·5	0·138
44	1·74	3·8	0·150
48	1·90	4·1	0·161
52	2·07	4·4	0·173
57	2·25	4·8	0·189
62	2·46	5·2	0·205
68	2·69	5·7	0·224
74	2·93	6·2	0·244
81	3·20	6·7	0·264
88	3·48	7·3	0·287
96	3·80	7·9	0·311
105	4·15	8·6	0·338
115	4·53	9·3	0·366
125	4·94	10·2	0·401
137	5·38	11·0	0·433



NOTE:- PAD THICKNESS IS ASSUMED TO BE APPROX. 0·3L.

Figure 1. Maximum Allowable Hole Size in Thrust Pads.

From the bearing point of view, thermocouples are preferred for temperature sensing, since they are more compact and are likely to be more accurate as sensing elements. The type of cable which is used is not critical, but there are advantages in using the mineral insulated stainless steel semi-rigid type, as it combines many of the advantages of the flexible and rigid types.

POSITION OF SENSORS

Temperature gradients within bearings can be very high—both across the surface of the bearing and through the depth (thickness) of the pad or shell (i.e., experimentally determined gradients within a thrust pad are shown in Figure 3). Measurement of the true maximum temperature, which occurs on the bearing surface, is thus difficult, requiring a grid of sensors to enable cross-plotting to find the true peak. While the maximum temperature might be required as a check on the correlation between predicted and actual performance on a newly designed machine, there is no real benefit in trying to measure the maximum temperature on a production machine.

Arranging limited instrumentation to attempt to record the maximum bearing temperature may not give the best (safest) monitoring data. For example, consider the temperature distribution in a conventional cylindrical bore bearing. In the circumferential direction, the temperature distribution will have the form shown by line A in Figure 4. The temperature rises from the position of the oil entry gutterway, past the load

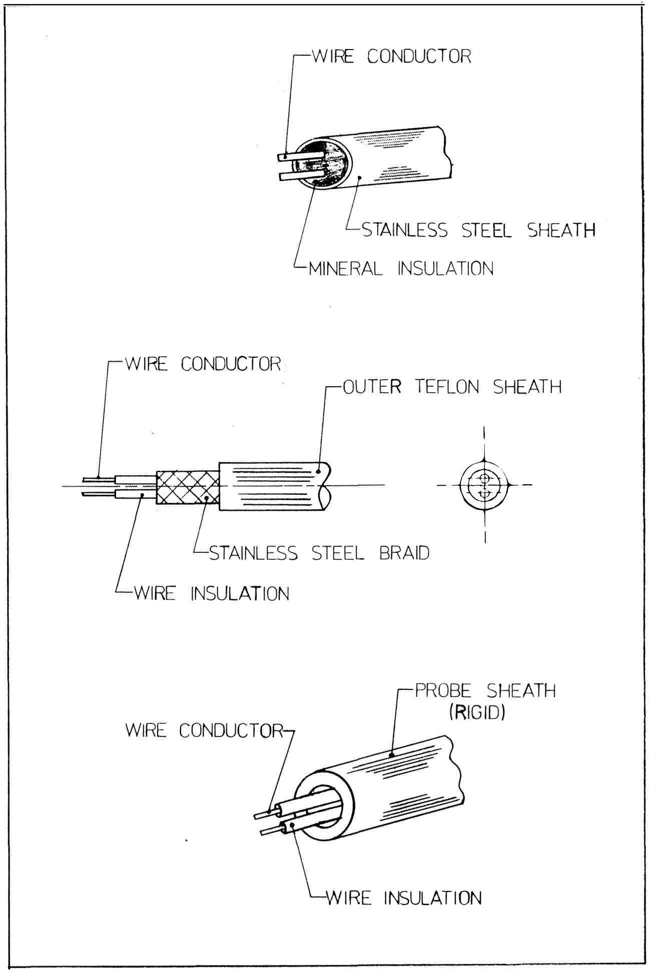


Figure 2. Cable Types for Temperature Sensors.

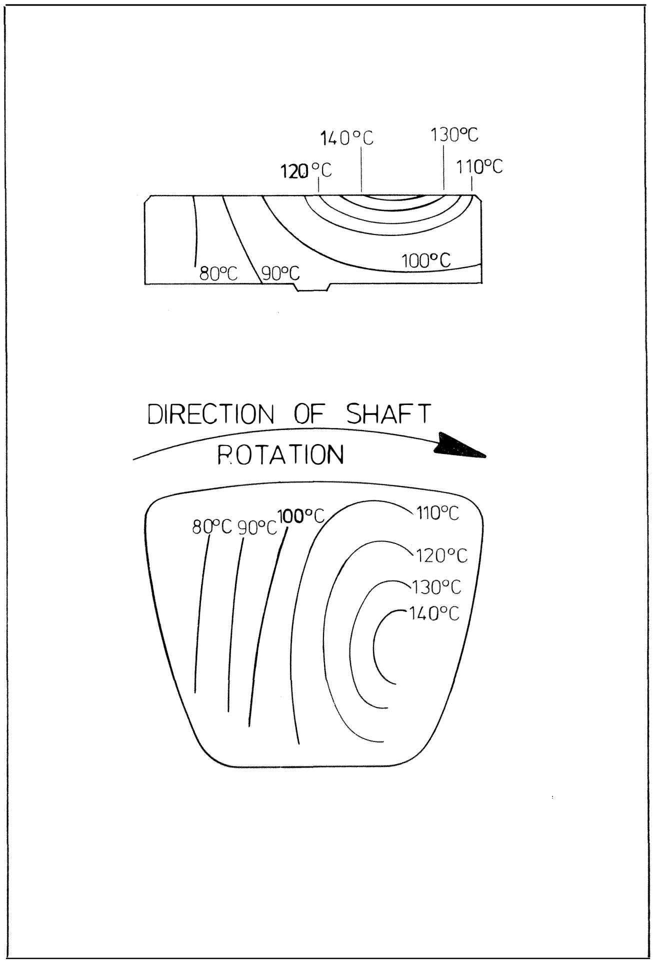


Figure 3. Typical Temperature Gradients in a Thrust Pad.

line position, peaking at approximately the point of minimum film thickness. The angle between the load direction and this minimum film thickness (the attitude angle) is likely to vary from 25° to 40°, and temperature measurement to determine the maximum bearing temperature needs to be at this angle from the load line. However, if the film thickness in the bearing is now reduced, either by an increase in load or perhaps due to damage to the lining surface, then the minimum film thickness will be reduced, the temperature will rise, but the attitude angle will be reduced. The resulting temperature distribution might be as shown as line B on Figure 4. The temperature which would be measured at the original minimum film thickness point in this example would actually decrease, even though the actual maximum temperature has increased. In many instances these curves do not actually cross, but the increase in temperature seen at the original minimum film thickness point could be considerably attenuated from the true maximum. However, if temperatures are measured at the load line position, then a rising temperature will be recorded throughout any load increases. If changing conditions within the machine can alter the resultant direction of the load, then several sensors must be placed around the bore of the bearing. A further advantage of placing the sensor at the load line is one in which the bearing instrumentation is then independent of the direction of shaft rotation.

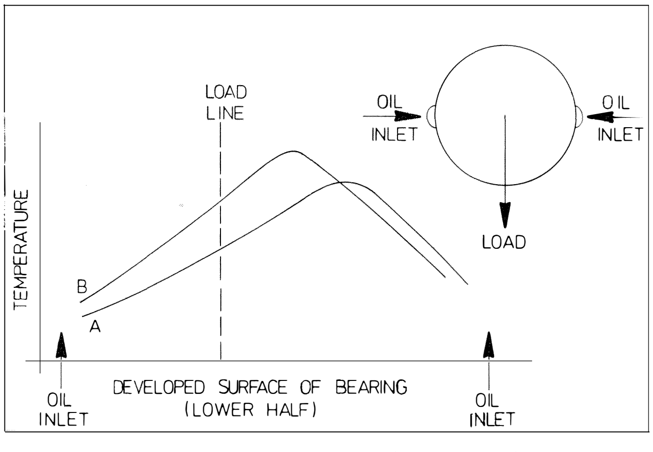


Figure 4. Temperature Changes in Plain Journal Bearings.

The fundamental guideline is to position sensors as close as possible to the externally applied load line or, to be more precise, the position on the bearing where breakdown of the film between the bearing and the shaft or collar could be expected to occur. This point is well defined in the simpler types of bearings, but can be less obvious where extensive lobing of the film shape exists due either to manufacture or to thermal mechanical distortions in operation.

In tilting-pad journal bearings, where the majority are bidirectional (center pivot), there is a preference to place sensors over the pivot. This preference is reinforced by the practical difficulties often encountered if sensors are placed nearer to the trailing edge where the maximum temperature occurs.

In tilting-pad thrust bearings, the surface profile deflects under load, so the sensor should be placed approximately midway between the pivot position and the trailing edge of the pad in the circumferential direction. Radially, the optimum position will lie between the center of the pad and midway between the center of the pad and the outside edge. This combined circumferential/radial location is commonly called the 75/75 position, as shown in Figure 5. There is probably not a lot of choice between a center radial position and the 75/75 position, since the location of film breakdown or maximum pad temperature can alter, depending on design and operating conditions. The 75/75 position will usually give a satisfactory reading. If the machine can operate in both directions of rotation, or a single design of pad is to be used for both directions, then the sensor should normally be positioned over the pivot (50/75 position in Figure 5).

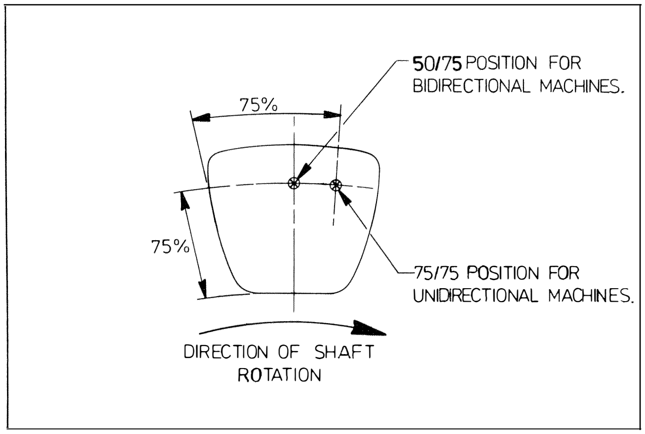


Figure 5. Suggested Temperature Measurement Points in a Thrust Pad.

The point at which a monitoring temperature sensor should be located is:

Journal bearings	
Cylindrical	at the load line position
Profiled	at the position of closest approach of the surface (maximum wall thickness position) nearest to the load line (if loading is symmetrical between lobes, then instrument the lobe which is downstream of the load line)
Tilting-Pads	directly over the pivot position, on the most heavily loaded pad (the downstream pad if the applied load is between two pads).
Thrust bearings	
Plain	on the flat (highest point of the bearing) lands
Tilting-Pads	In the 50/75 position for bi-directional machines. In the 75/75 position for unidirectional machines.

Care must also be taken with the positioning of sensors in the other direction—the axial position in journal bearings, which pad or pads in thrust rings.

The axial temperature distribution in a journal bearing is very dependent on the alignment between the shaft and the bearing surface. The measurement of temperature near the two axial edges of a bearing, at the same angular location, provides an extremely sensitive measure of shaft alignment. Obviously, this will not be as true in tilting-pad journal bearings which have axial alignment capability.

In thrust bearings, significant differences occur in individual pads in the thrust ring, due to misalignment and machining tolerances. Even on tilting-pad thrust bearings of the self-aligning type, these differences can still be significant [1], and it is good practice to place sensors in at least two pads, approximately 180° apart. Since running cables across the split lines of bearings should be avoided, a less than optimum spacing is often used.

As temperature gradients through the thickness of a bearing can be high, the precise position of the sensor from the active surface of the bearing can greatly influence the observed temperature. Some experimental results from a tilting-pad thrust bearing which illustrate the magnitude of this gradient are shown in Figure 6. Once again, it is not advisable to try and record the maximum temperature by arranging for the sensor to be as near as possible to the bearing surface, since any features within the relatively low strength lining material (normally whitemetal) can affect the integrity of the bearing. It is far safer to arrange sensor drillings so they remain within the backing material (usually steel), and accept that the true surface temperature will be higher.

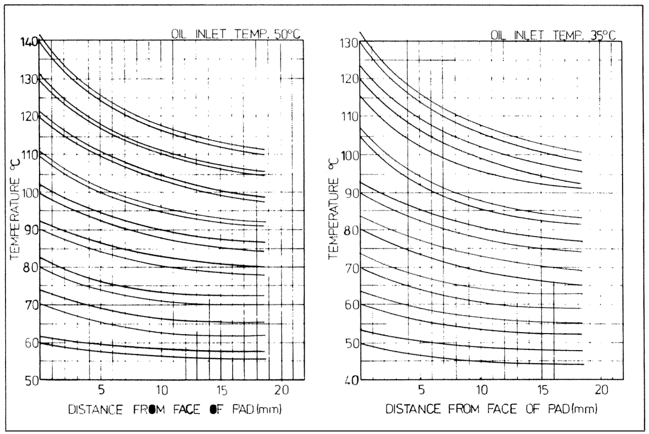


Figure 6. Variation of Temperature through the Thickness of a Thrust Pad.

METHOD OF INSTALLATION

The choice of installation method concerns the connection of the sensor tip in the bearing to the outside of the machine (i.e., the cable run) and the method of retention of the sensor in the bearing.

Connection of Sensor to Outside of Machine

The main choice in connecting a sensor to a bearing is whether the sensor is to be removable from outside the machine, or whether access to, and partial dismantling of, the bearing is required before the sensor can be removed. Some typical examples of these two methods of installation are shown in Figure 7.

It is generally preferable to use externally removable sensors, but the following points must be borne in mind:

- The sensor must be rigid or semi-rigid. This can be a problem in tilting-pad bearings where it is important that the sensor does not restrict the pad movement. In addition, the size of this type of sensor may not be compatible with the size of the pad (Figure 1).
- The sensor cannot be bonded or embedded in the surface of the bearing.
- The straight drilling required for the sensor may make it difficult to locate the sensor in the desired position in the

bearing, due to constraints imposed by the design of the outside machine casing.

- The advantage of using a flexible cable installation (Figure 7) is that the sensor can usually be placed where it is wanted in the bearing and can, if necessary, be embedded or bonded to the bearing. Problems which must be considered are:
- Cables must be sufficiently flexible to enable installation and/or dismantling of the bearing without breaking.
- The cable runs are sometimes difficult to arrange in the bearing, due to the lack of space. The assembly and dismantling procedures must involve minimum disturbance of the sensors and cables. This can be particularly difficult to arrange on a split tilting-pad thrust bearing, with two or more pads instrumented. One way that this can be accomplished is shown in Figure 7.
- The exit of the cable from the bearing housing requires some form of gland in most cases. Usually, this can best be achieved at the joint face of the housing, although sometimes it is provided by means of a gland hole. This latter system can be awkward in terms of assembly and/or dismantling.

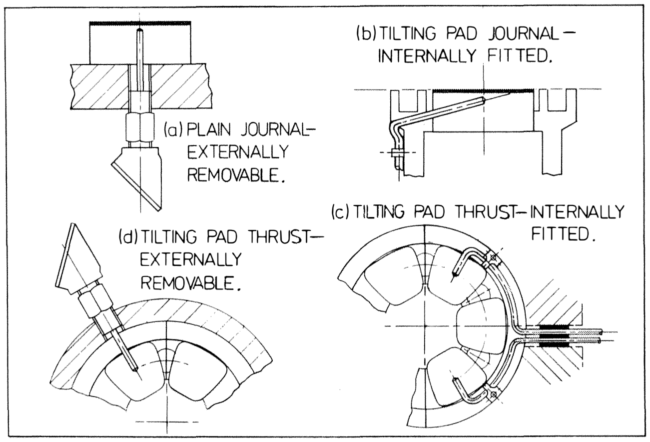


Figure 7. Methods of Fitting Temperature Sensors.

Retention of Sensor in Bearing

The retention method is obviously very dependent on the location of the sensor, either in the bearing surface material (usually whitemetal), or, preferably, in the bearing backing material (usually steel).

If the sensor is in the whitemetal, in all except the largest bearings, it must be embedded in the whitemetal itself by a puddling process. This process, which necessitates disturbance of the bearing surface, requires a specialized and skilled procedure for installation. In addition, placement of sensors near the surface may result in damage to the shaft as well as the sensor if wear occurs during low speed operaton.

If the sensor is to be installed in the pad or bearing backing material, it can either be:

- bonded in position
- a push-in fit with spring loading
- a push-in fit with clip retention.

These three methods are shown in Figure 8. The bonded sensor is the most positive, but will involve complete replacement of the bearing or pad if the sensor becomes faulty. A spring loaded sensor with a push-in fit is a good compromise but is not suitable for small bearings, due to the relatively large hole required to take the spring features. For example, on tilting-pad thrust bearings, a spring loaded system is not generally feasible below a 75 mm (3 in) pad size. A push-in type installation with external clips is generally the most practical for general industrial use, as it gives a good reading and is easily replaced if faults occur. A suggested fitting method for such a sensor is shown in Figure 8. It is very important that the active part of the sensor is firmly in intimate contact with the bearing material, otherwise inaccurate results can be obtained.

An externally removable sensor, preferably spring loaded, should be used, provided that the restrictions detailed can be accommodated. If they cannot, then an internal push-in type of installation in the bearing backing (either clipped or spring loaded) is the next best choice.

ALARM/SHUTDOWN SETTINGS

Temperature readings from sensors are normally used to activate machine alarm and shutdown procedures. It is recommended that these settings should be 10°C (18°F) and 15°C (27°F), respectively, above the maximum recorded temperature at the sensor during normal operation. While predictions can be made for these in advance, it is essential that final values are established after prototype running. If too high a value is used, alarm sensitivity is lost, while if too low a value is used, spurious alarms will occur in normal service. Note that these alarm and shutdown temperatures are normally well below the failure limit for the bearing lining material.

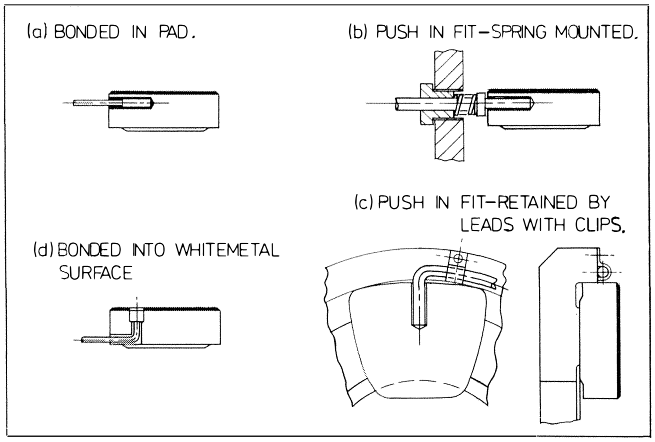


Figure 8. Sensor Retention Methods.

CONCLUSION

It is recognized that bearing temperature instrumentation may have to be designed to suit particular machine requirements. However, many of the variations seen in practice may not be necessary. It is hoped that the comments presented herein will help engineers in their choice of sensor systems and may make some contribution to establishing industrial standards.

ACKNOWLEDGEMENTS

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REFERENCE

1. Leopard, A. J., "Tilting Pad Bearings—Limits of Operation," ASLE Lubrication Engineering, *32* (12), pp. 637-644.