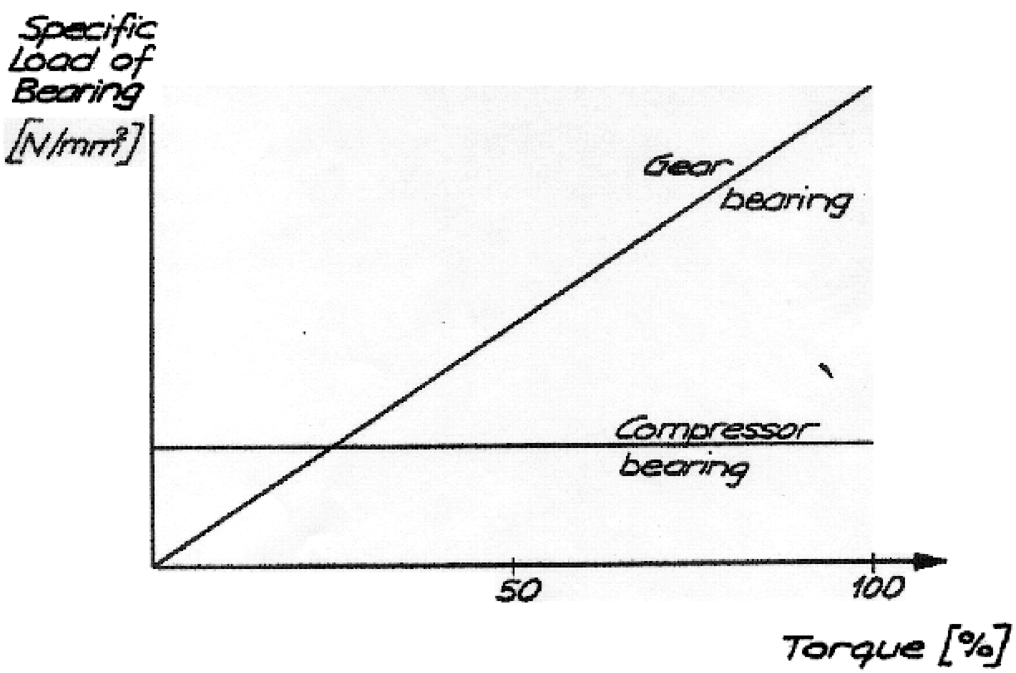
Bearings for High Speed Gears

1 Requirements for Radial and Axial Bearings

The speed and power of rotating machines is continually increasing, whereby the requirements for speed increasing and reduction gearboxes or strictly speaking for their gears and bearings are also increasing.

Safely supporting a high speed compressor rotor, for example, in trouble-free operating radial or journal bearings is not at all a small problem, but in comparison, supporting a gear pinion, which is coupled to the compressor rotor involves more problems. While the load on a compressor radial bearing is always constant, depending only on the weight of the rotor, the load of the pinion radial bearing varies with the compressor power between zero and a maximum. This maximum load is several times higher than the weight of the rotor (*see figure 1*).

Figure 1: Bearing Load Characteristics



At full load the pinion radial bearing has to function under the combination of very high speed and very high bearing pressure, which would call for a radial bearing with a high load carrying capacity. However such a high capacity radial bearing would not have a very high stability.

On the other hand there is also the other extreme condition, which is operation of the radial bearing under no load conditions; especially during final shop testing. As the pinion normally is pushed upward by the tooth contact force it is possible that, when partially loaded, this force is about equal to the weight of the rotor and the resulting loading on the radial bearing in this particular case may amount to zero. These conditions would call for another type of radial bearing; a very stable one, but with a very low load carrying capacity.

Finally, partial load conditions, anywhere between zero and full load can occur, including partial load during the special conditions of run- up and run-down, under which the additional phenomena of transient vibrations may appear.

Unfortunately, we cannot use two types of radial bearings for one rotor; we have to use one type which must meet the operating requirements at all load conditions of the machine.

In addition to the loading and stability constraints of the journal bearing, given above, the aspect of lateral vibration must also be considered. The journal bearings of every rotor are very important elements of the lateral vibration system, which determine their vibration behavior.

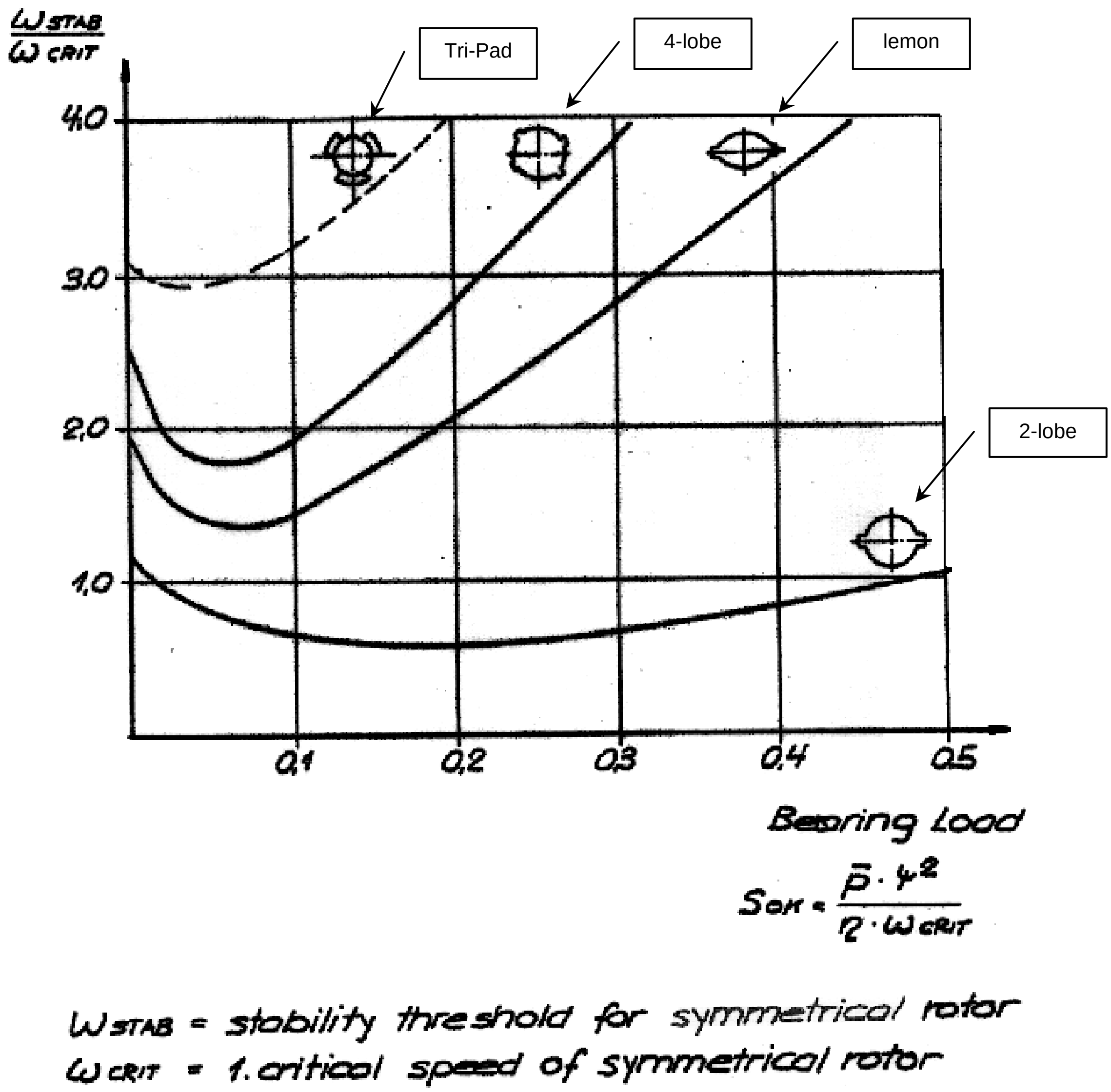
The static bearing characteristics such as oil film thickness or temperature change greatly with load. Similarly the dynamic bearing characteristics, such as the stiffness and damping values also are strongly influenced by the power transmitted by the gear. This fact can be of great importance for the review of the dynamic behavior of the gear rotor.

The high loading of the gear bearings at maximum power requires these bearings to be rather large in size, but this requirement leads to a high circumferential speed in the bearing. As the bearing length is not unlimited, the dimensions of a gear bearing are always a compromise between the bearing load and the circumferential speed. The relatively large size of these bearings is advantageous in regard to vibration because of the high stiffness and damping coefficients it provides. The damping of these bearings is especially excellent so that, for example, the passage through the critical speeds during the start-up and run-down cannot be observed.

The positive effect of the oil film which actually makes the supporting of high speed rotors possible unfortunately also has certain limits.

Depending on its geometrical form, every bearing possesses a limiting speed, called threshold of stability, beyond which the oil film proper- ties, especially at low load conditions have a destabilizing effect (*see figure 2*). Operating beyond this speed threshold is not possible.

Figure 2: Bearing Stability Characteristics



Fortunately there is an exception: the tilting pad bearing does not have the same strong threshold of stability as the sleeve bearing

To summarize, it can be said that the high-speed journal bearing for use in gears, must have the following properties:

1. Safe extended operation at the combination of high speed and high bearing pressure (i.e. vibration levels, temperature and oil film thickness must be correct.)
2. Sufficient damping within the whole speed and load operating range (i.e. acceptable vibration amplitudes even if operating at critical speeds must not be exceeded.)
3. Operation within the stable range of the bearing (threshold of stability must not be reached under any possible conditions of operation.)

The axial, or thrust, bearing is not as critical as the journal bearing, as it has usually only to carry the thrust from helical gearing and from the coupling. However, sometimes it is also necessary to support the thrust from the driving or driven machine.

Since the speed of the thrust bearing can be very high and since the axial load can also reach high values, the limitation of this type of bearing is primarily the temperature.

Considering all which has been said about gear bearings it is not surprising that the bearings, as well as the gearing, often belong to the limiting parameters of a high-speed gear.

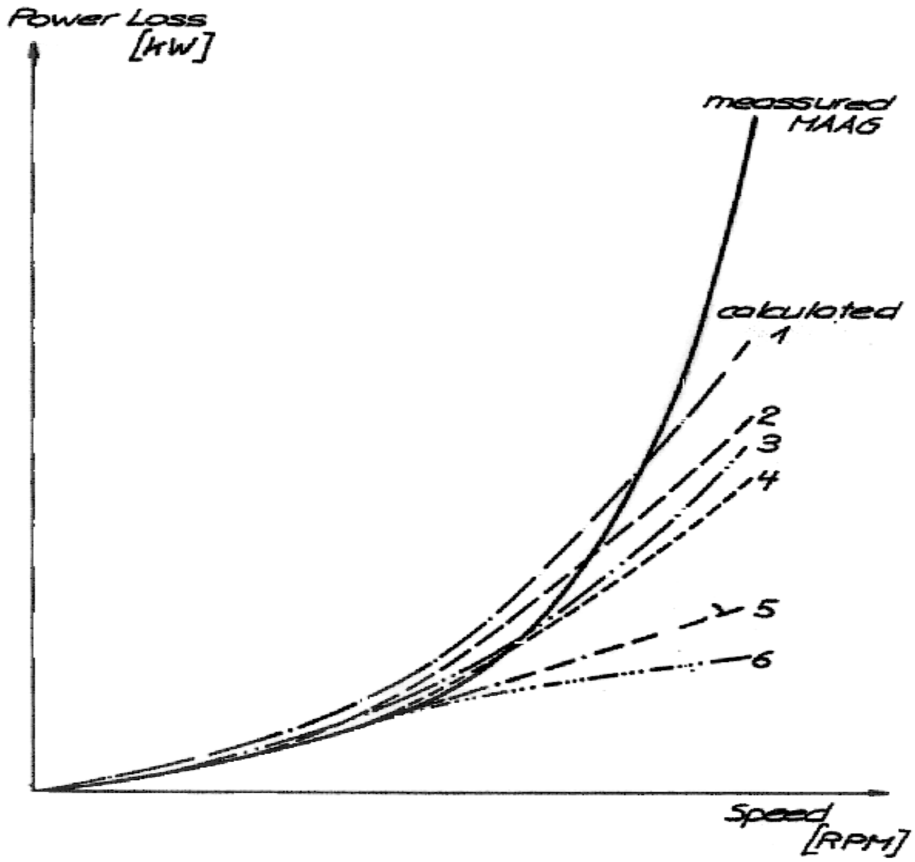
2 MAAG Bearing Test Stand

MAAG created a program for the lay out and calculation of the radial bearings, and conducted a test program.

The testing comprised of a gear housing with two radial bearings, a plain shaft was rotated and the temperatures, oil flow and the power losses were measured; of course without the influence of load. Then the results of these measurements were compared with the calculated values using six different calculation methods.

As the example of the power losses shows, (*see figure 3*), the result of this comparison was totally unsatisfactory.

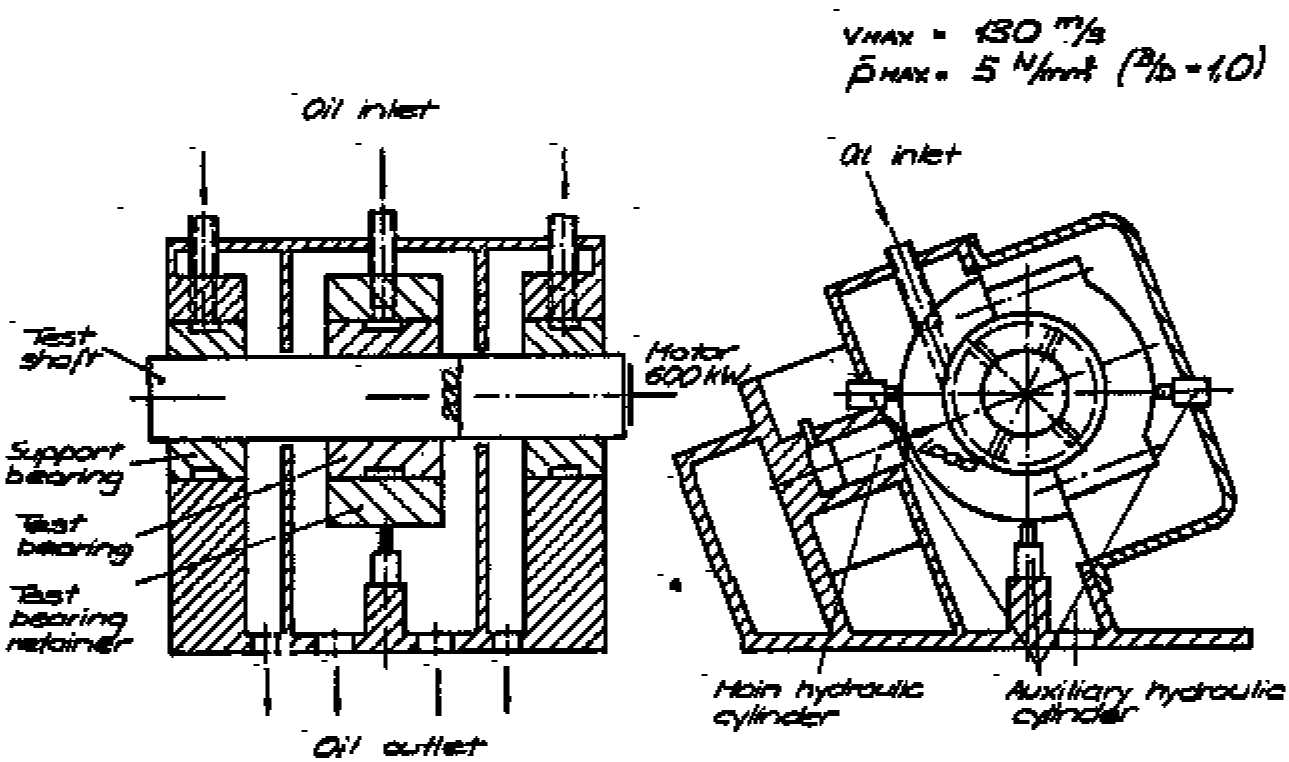
Figure 3: Bearing Power Loss: Calculated and Measured Values



From this experience it was concluded that it was necessary to build a radial bearing test stand at MAAG in order to be able to measure all the properties of MAAG bearings so that they could supplement and, respectively, correct the theoretical calculation methods with actual measurement results. The construction of a bearing test stand facility at MAAG also allowed for the possibility for the development of new bearing types.

The test stand (*see figure 4*) consisted basically of housing, with two support bearings, between which the single test bearing was mounted on a common shaft. The test bearing can be loaded hydraulically in the radial direction. The position of the bearing was rotated between test runs to simulate the various possible load directions

Figure 4: Test Stand



Journal bearings of any design were tested on the MAAG bearing test stand. The following parameters can be changed:

- Diameter
- Length
- Clearance
- Speed
- Load and load angle
- Pressure and temperature of oil inlet

The following dependent variables were measured:

- Power loss
- Temperature distribution within the bearing
- Temperature of oil outlet
- Minimum oil film thickness
- Shaft displacement and angle
- Vibration of journal (and pads in the case of tilting pad bearings) Clearance curve (at standstill)

The measured data was recorded by the data acquisition unit and processed by a computer. The results were automatically tabulated and plotted.

An evaluation of one test bearing required about 100,000 individual measured values.

Dynamic bearing properties were not evaluated quantitatively on the MAAG bearing test stand. Prof. Glienicke measured them for MAAG on a special bearing test stand at the Technical University of Karlsruhe, Germany. Each reading was conveniently represented by four stiffness and four damping coefficients. The results were stored in non-dimensional form for the calculation of the lateral vibrations of our gear rotors.

An important aim of the bearing test stand and of measurement in general was the possibility to obtain all the parameters, which were needed for the various computations, such as temperature, oil flow, power losses, and dynamical bearing coefficients. Measured bearing data led to improved computations, compared with results of purely theoretical methods. This ultimately led to improved bearing characteristic and rotor dynamic computations because many important bearing parameters exist which cannot be sufficiently determined by pure theoretical methods. An example of a parameter which falls into this category is the change of the bearing geometry due to the thermal and mechanical deformation of the bearing.

3 Present Stage

The present stage of the bearing applications on Maag (now ref. to as Renk-Maag) gears is outlined in the following paragraphs.

For journal bearings Renk-Maag continues to exclusively use bearings of its own design. Renk-Maag sources 2-, 3- and 4-lobe journal bearings depending on the application, (*see figure 5*). For very high speed applications Renk-Maag uses tilting pad radial bearings, with 3 pads, i.e. with one larger main pad, and two smaller auxiliary pads, (see figure 6).

Figure 5: Renk-Maag 2, 3 and 4 Lobe Bearings:

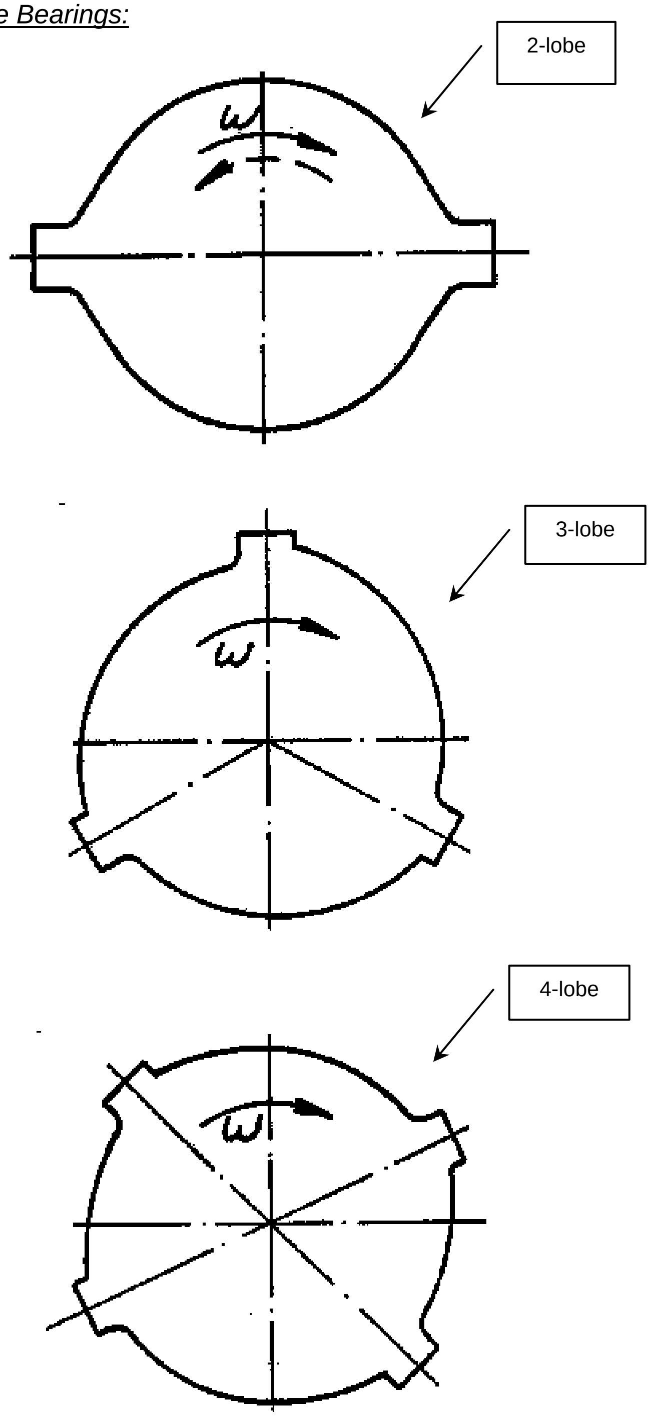
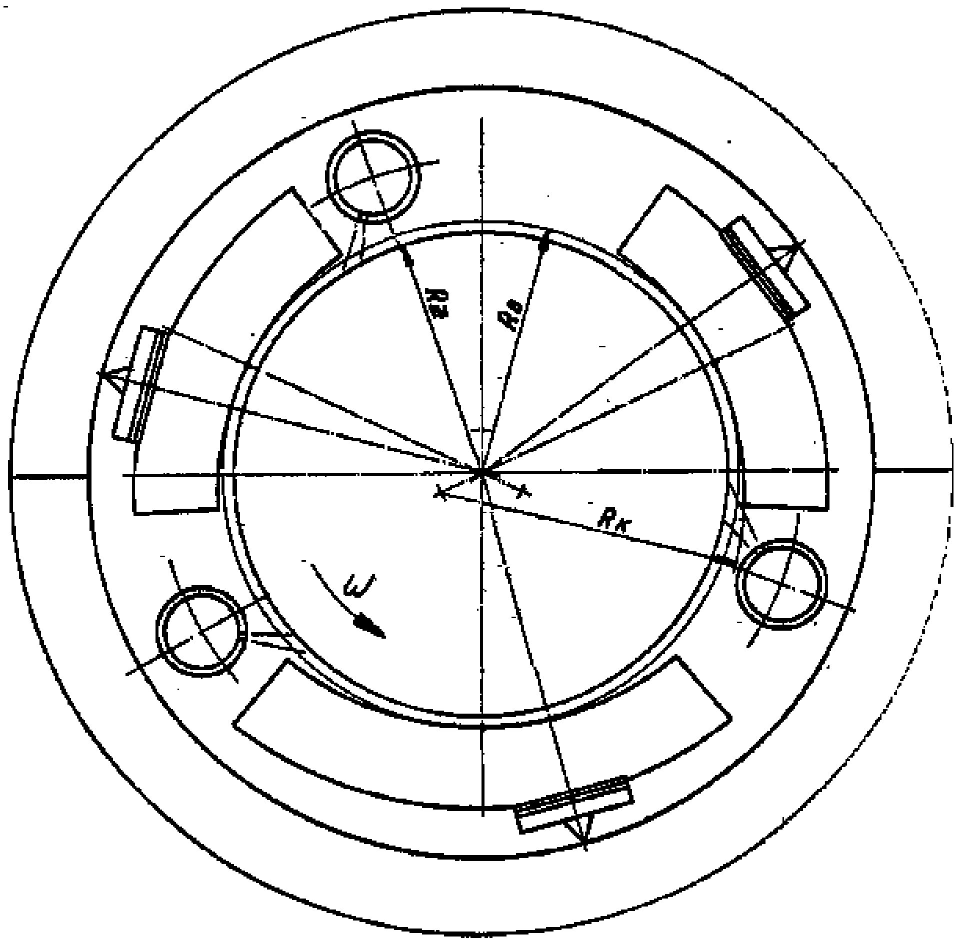


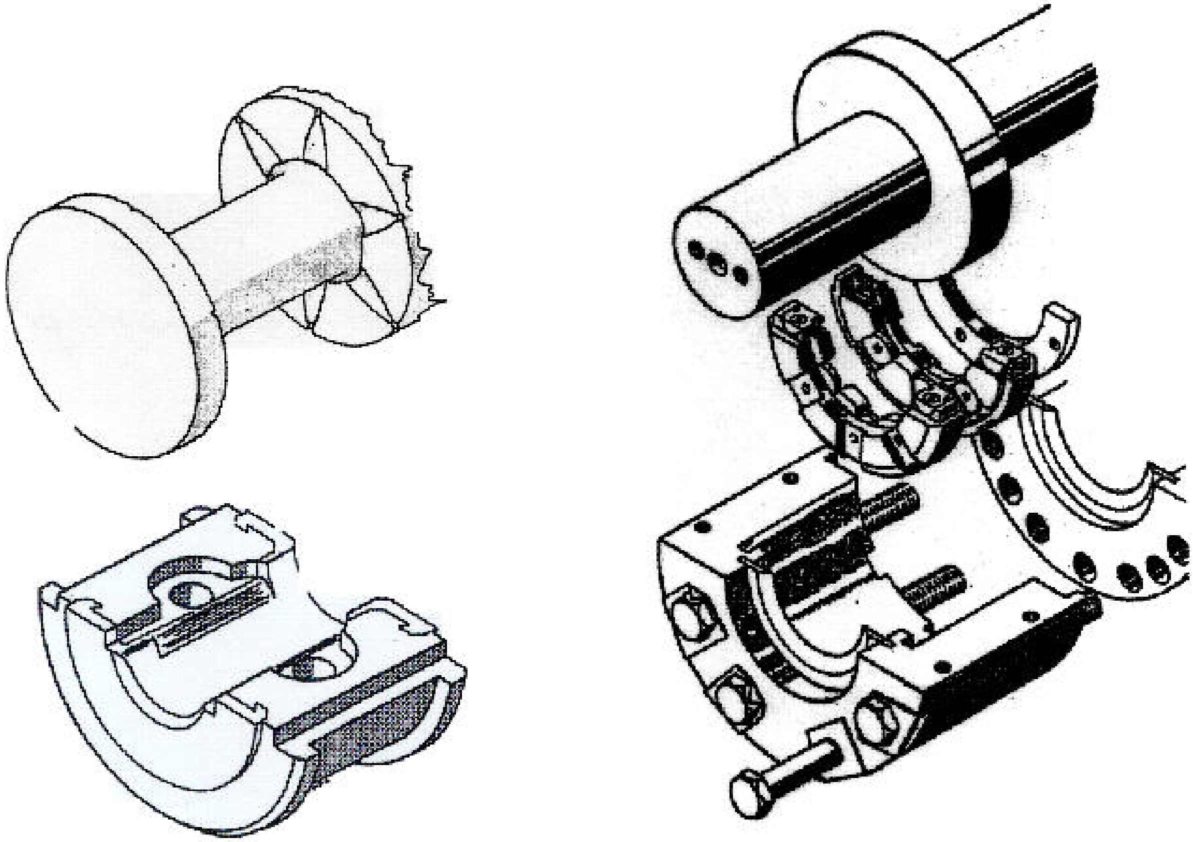
Figure 6: Renk-Maag Tilting Pad Bearing Schematic:



By changing the shims of the individual pads it is possible to adjust, not only the clearance of the bearing, but also of the tooth contact pattern during the assembly of the gear. The lubricating oil is injected directly on the journal for each pad.

Thrust bearings used on Renk-Maag gears are of two major types (*see figure 7*). For lower and intermediate power and speed applications, taper-land thrust bearings, which are integrated in the radial bearings, are usually used. For all other applications tilting pad thrust bearings, purchased from renowned manufacturers, are used. Flood lubrication of the tilting pad thrust bearings is used, if speeds permit. For very high speeds, direct lubrication of the pads is employed.

Figure 7: Taper-land and Tilting Pad Thrust Bearing



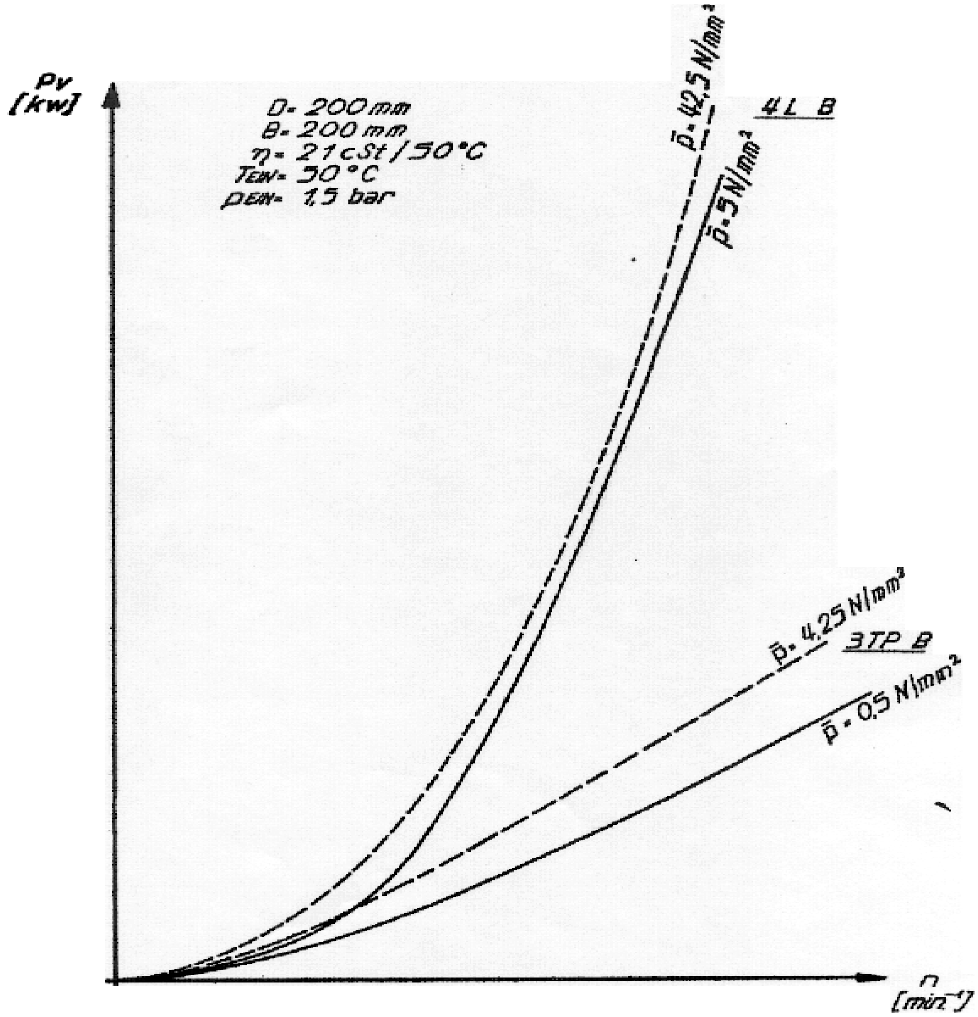
4 Future Development

Renk-MAAG's effort in the field of sliding bearings is aimed at the:

- Reduction of power loss
- Increase of load capacity
- Reduction of the maximum bearing temperature

The first goal can best be reached by the tilting pad journal bearing as shown previously (*see figure 7*). Due to the reduced surface area compared with the fully enclosed bearing, and because of a greater speed range in which the oil flow remains laminar, a power loss reduction of between 50% and 70% is possible (*see figure 8*).

Figure 8: Power Loss Comparison Lobe Bearing vs. Tilting Pad Bearing Measured Values



An increase of load capacity is offered by the Tri-Pad bearing. The main pad of this tilting pad bearing has a width/diameter ratio > 1 and is divided into two halves by a central groove.

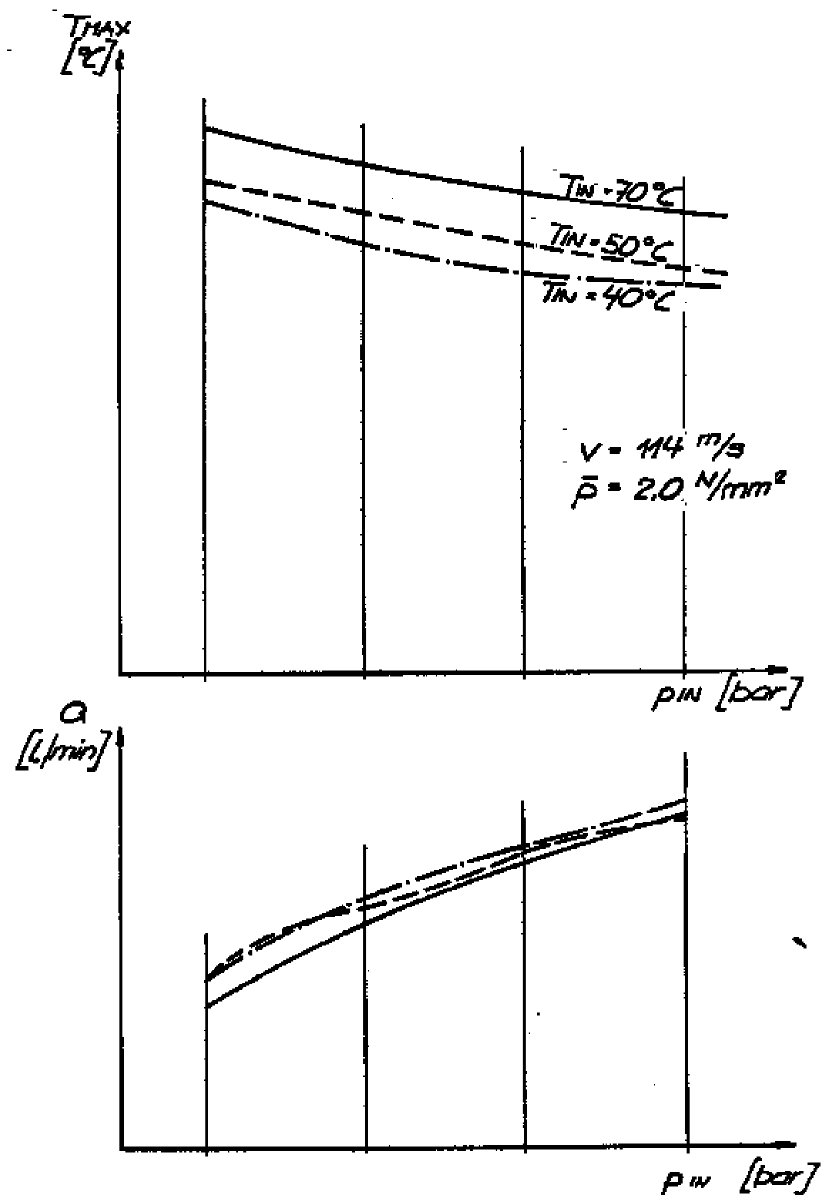
One principal aim of the bearing development is the reduction of the maximum bearing surface temperature. White metal is still the best surface layer for slide bearings, because of its excellent conformability. However, it has one disadvantage: The maximum allowable temperature is relatively low.

On the bearing test stand successful tests of relatively short duration have been carried out with oil film temperatures up to 160° C (320° F). However, for extended operation the safe temperature limit of ≅ 130° C (265° F) should not be exceeded.

Some customers are even more conservative and have set this limit at 93ºC (200ºF). For high-speed gears, it is now possible to remain within these limits.

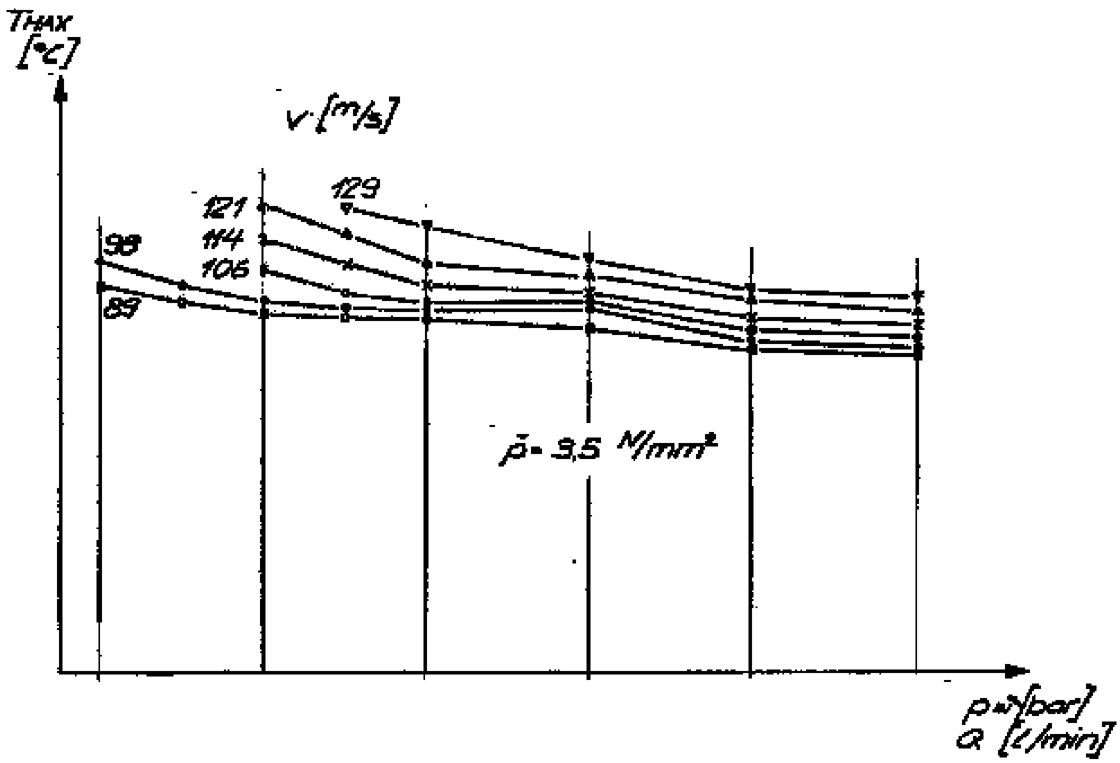
MAAG's research program showed some positive results. For example with the 4-lobe bearing the increase of the lube oil pressure at the bearing inlet from 1,5 to 3,0 bar has reduced the maximum white metal temperature by about 9ºC (with certain combinations of speed, and bearing pressure). However, this results in an oil flow increase of approximately 20% (*see figure 9*).

Figure 9: MAAG 4-Lobe Bearing. $\tau_{max} : Q = f(p_{in})$



In the tilting pad bearing an increase of oil flow by the same percentage reduces the maximum surface temperature to a larger extent. Here, for example, a reduction of 11ºC was achieved with a bearing of much higher speed and specific pressure as the 4-lobe bearing (*see figure 10*).

Figure 10: MAAG Tilting Pad Bearing $\tau_{max} : Q = f(p_{in})$



Factors which influence the maximum surface temperature and which must be optimized are:

- Location of the tilting pads relative to each other and relative to the load vector.
- Location of the pivot of the pad.
- Direction and method of the lube oil injection.

5 Some Typical Results

Referring to figures 11 and 12: These figures represent "bearing pressure vs. bearing speed" with maximum surface temperature isotherms. These diagrams have resulted from test stand measurements and are a practical aid for the bearing designer.

Figure 11: Renk-Maag 4-Lobe Bearing Temperature Characteristics

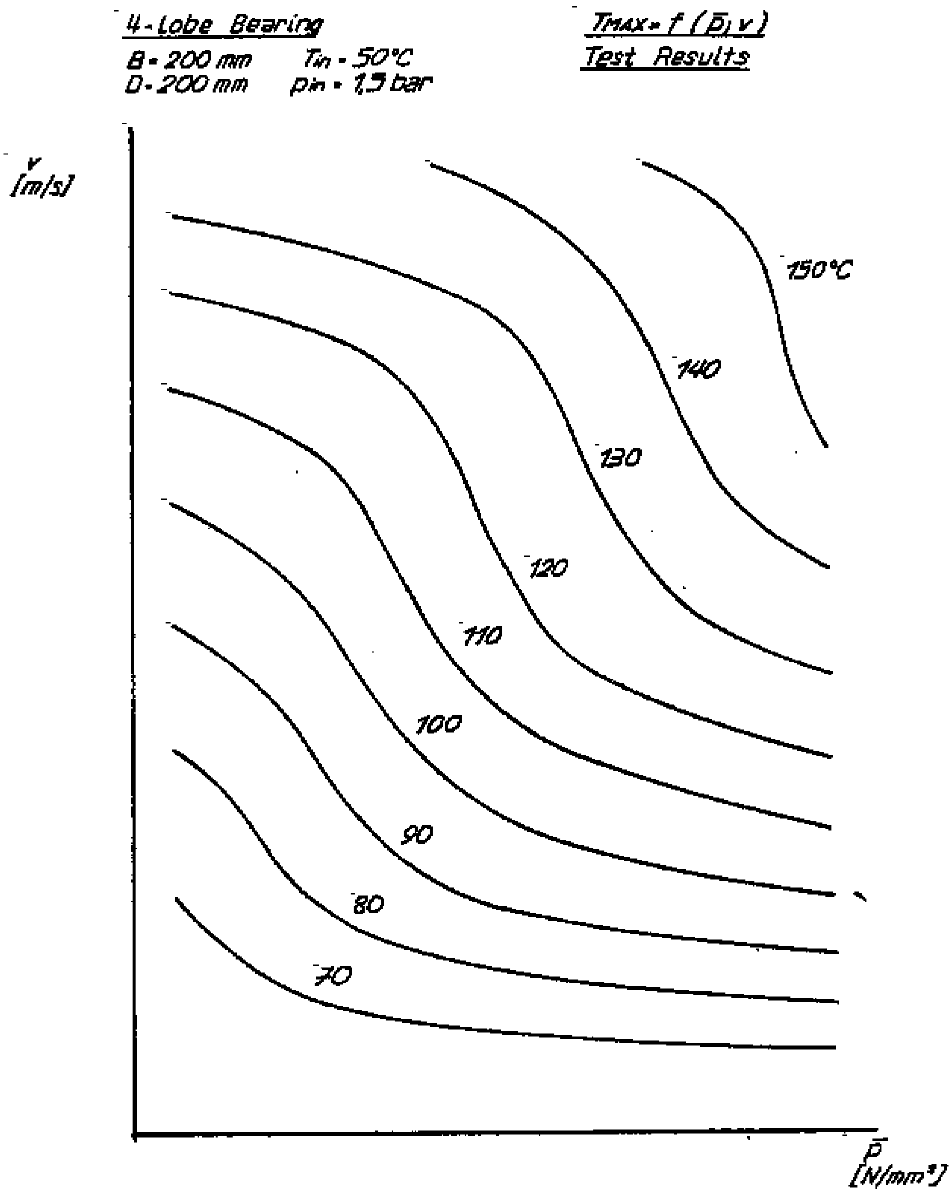
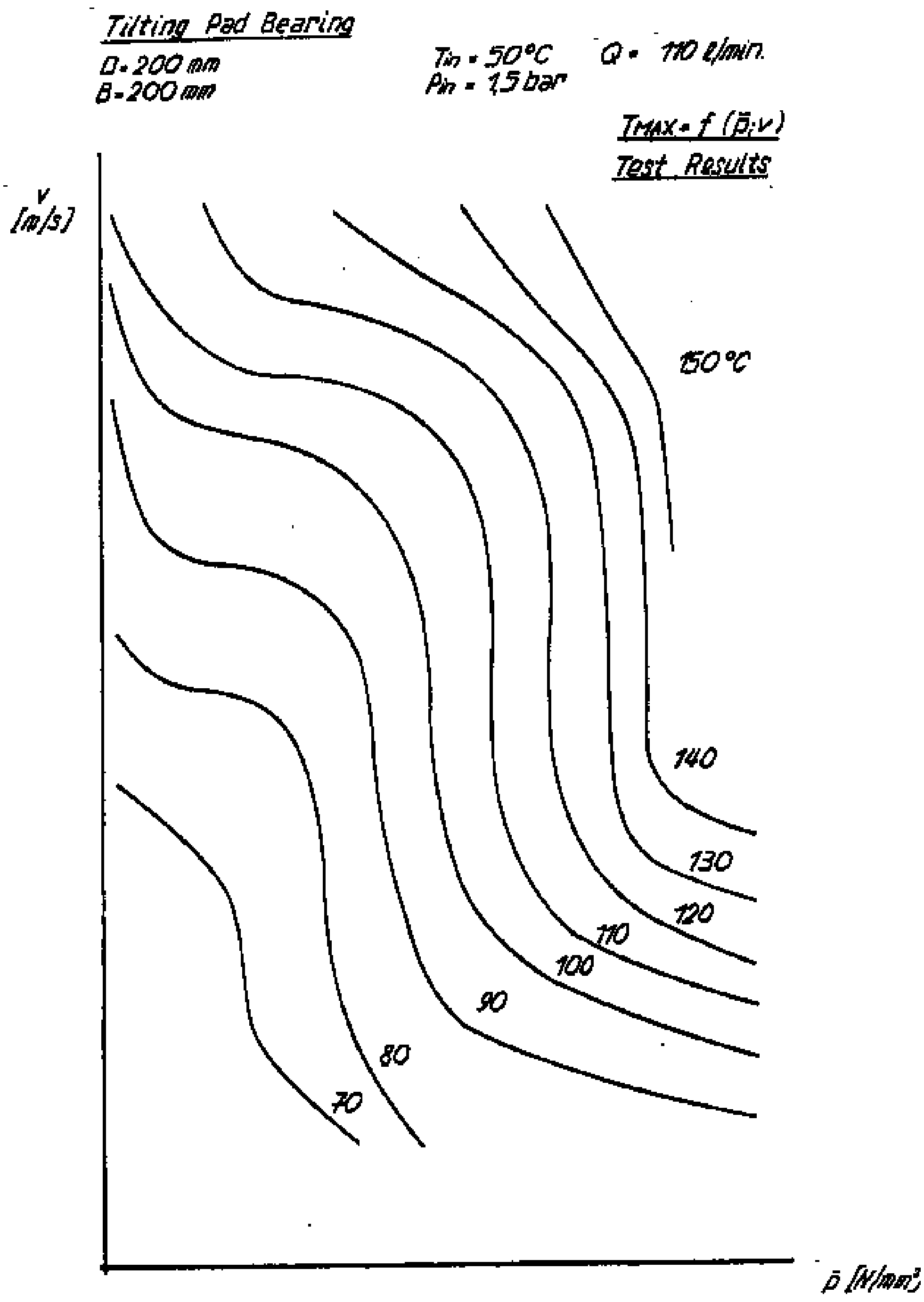
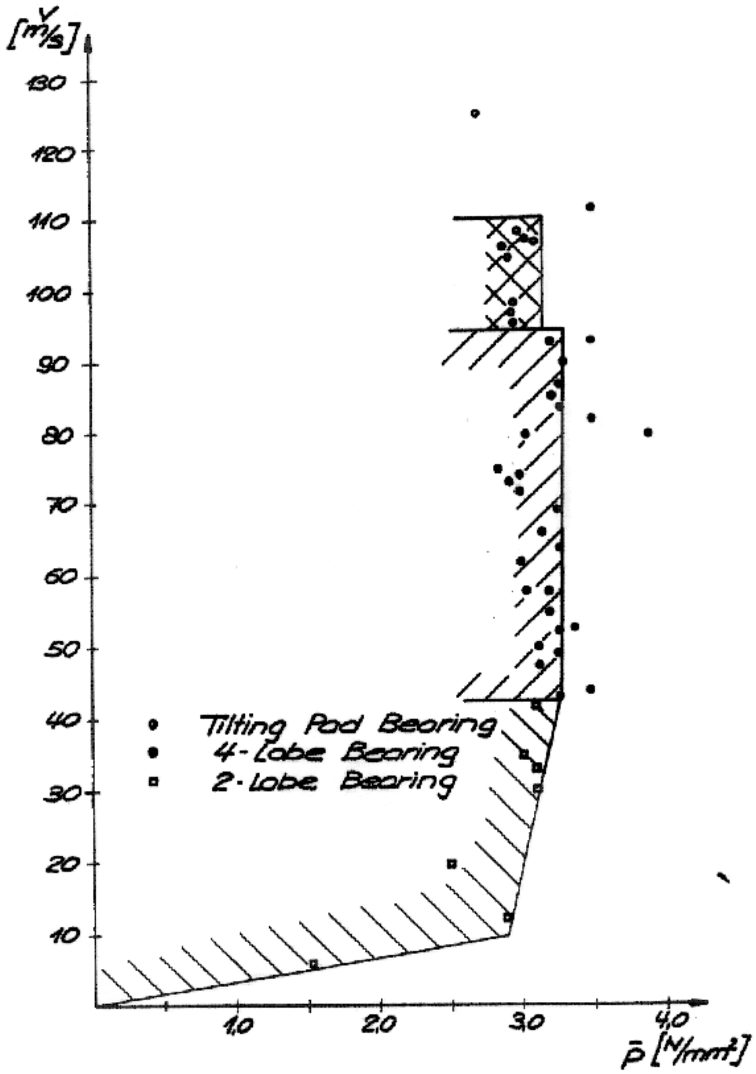


Figure 12: Renk-Maag Tri-Pad Bearing Temperature Characteristics



The last graph (*see figure 13*) shows some typical and some extreme applications of our journal bearings.

Figure 13: Some Typical, and Extreme, MAAG Radial Bearing Applications



As can be seen, Renk-Maag is seriously tackling the future challenges and thereby hopes to be prepared for every requirement which our customers may present.