FORECASTING THE LIFE OF ROCK-BIT JOURNAL BEARINGS

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SUMMARY

This paper describes an analytical procedure for forecasting the life expectancy of rock-bit journal bearings. Actual performance data and reliability analyses are used to establish empirical relationships and graphs that relate risk of bearing failure to operating parameters and drilling cost. The paper was originally published in *SPE Drilling Engineering*, June 1990 (Volume 5, No. 2).

INTRODUCTION

Although most journal-bearing rock bits are retired with effective bearings, the risk of bearing failure continues to be a major concern because it can cause cutter loss and result in an expensive and time-consuming fishing job. As a consequence, many bits are retired with useful lives remaining, and operating practices are often tempered to yield increased bearing reliability at the expense of penetration rate. These circumstances led to the development of a technique for estimating the risk of bearing failure through analysis of actual bit performance in commercial drilling applications.

CAUSES OF ROCK-BIT JOURNAL-BEARING FAILURE AND MEASURES OF BEARING LIFE

The effectiveness of a rock-bit bearing is controlled by the seal, the lubrication system, and the bearing itself; failure of any of these constitutes a bearing failure. Lubrication system failures are very rare; usually the bearing or the seal fails.

For approximately 20 years, the O-ring[1] has been the most popular seal. As Fig. 1 illustrates, it is squeezed between the stationary journal and rotating cutter (cone). This arrangement causes continuous wear at one or both of the contact surfaces, and this wear eventually allows drilling fluid to enter the bearing. Such wear is always present in a used bit, but significant bearing wear is rarely observed in the absence of seal leakage. Thus, when a bearing failure is experienced in an O-ring sealed bit, seal failure is normally considered to be the cause.

Fig. 2 shows an alternative to the O-ring, the metal-face seal.[2] This design provides a dynamic seal between the contacting faces of two metal rings supported and held in contact by compressed O-ring energizers. With this arrangement, the O-rings act as static seals and do not experience continuous rubbing. In addition, the high wear resistance and low frictional drag afforded by the metal rings permit these seals to operate effectively over a range of surface speeds and ambient temperatures much broader than the range of the O-ring.[3,4] As a result, bearing surface wear is currently the most common cause of bearing failure with the metal seal.

Sliding-contact wear is usually proportional to the product of contact pressure and distance traveled.[5] Thus, seal life should be a function of pressure between sealing surfaces, bearing size, and bit revolutions. Similarly, bearing life should be a function of weight on bit (WOB), bearing size, and bit revolutions.

Because seal contact pressures are controlled by design parameters rather than operating parameters, an appropriate measure of seal life for a particular bit size is the product of rotary speed and time of use or simply bit revolutions:

$$\lambda_s = 60\,v t_b = n \tag{1}$$

Bit size influences seal life because bearing diameter increases in proportion to bit size. This causes seal wear per bit revolution to increase as bit size increases. Part of the increase results from greater sliding distance and part results from higher surface speeds, which produce greater frictional heating and a rise in seal temperature.[6] The rise in seal temperature accelerates O-ring wear through a reduction in tensile strength,[7] as Fig. 3 illustrates. Of course, simultaneous use of high WOB and high rotary speed will also elevate bearing temperatures regardless of bit size, but damaging combinations can be avoided by keeping the product of WOB and rotary speed within limits established by bit manufacturers.[8] Poor bottomhole cleaning will also aggravate seal wear. Cuttings accumulation in the vicinity of the seal accelerates abrasive wear and inhibits cooling. Bit balling also inhibits cooling of the cutters.

Rock-bit journal-bearing wear is a complex phenomenon. Although the bearings are well lubricated, they seldom operate in a hydrodynamic mode because surface speeds are relatively low, and the magnitude and distribution of the applied loads vary significantly during each bit revolution. For these reasons, bearing materials and lubricants are selected for operation in a boundary lubrication mode.[5] Such operation is normally accompanied by very gradual wear, which does not interfere with bearing operation until increased clearances or accumulated wear debris promotes critical bearing or seal damage. Under rough running conditions, bearing failure may be caused by momentary overloads that promote localized seizures on the bearing surfaces. These seizures accelerate the wear process and inhibit the effectiveness of the solid lubricants in the grease. Obviously, both gradual wear and the likelihood of seizures increase as WOB increases.

Another condition that can promote bearing failure is reaming. This practice subjects the bearings to heavy inward-thrust loads, which must be carried by the cutter retention means. These means have lower bearing capacity than the surfaces that support normal drilling forces. Consequently, reaming can cause relatively rapid wear, and prolonged reaming can result in early bearing failure.

In the past it was common to assume rock-bit bearing wear proportional to WOB.[5,8-10] On the other hand, for contact between cylindrical surfaces, Hertzian analysis[11] predicts maximum contact pressure proportional to the square root of applied load. For the loading conditions that occur in rock-bit journal bearings, the Hertzian analysis is not always applicable,[12] but it is not unreasonable to assume that the Hertzian relationship may offer a better approximation of the proportionality between WOB and maximum bearing contact pressures. (The author is aware of an unpublished study of journal-bearing rock-bit life based on actual bit performance that shows bit life inversely proportional to a fractional power of WOB near 0.5.) Accordingly, the following relationship between contact pressure, WOB, and bearing dimensions was chosen for this study:

$$p_c \propto \left[\frac{W}{L}\left(\frac{1}{r_j} - \frac{1}{r_c}\right)\right]^{1/2} \tag{2}$$

As mentioned earlier, bearing diameter increases in proportion to bit diameter; the same is true for bearing clearances and bearing length. Therefore, Eq. 2 reduces to

$$p_c \propto \frac{W^{1/2}}{d_b} \tag{3}$$

Multiplying contact pressure and distance traveled then produces the bearing-life parameter:

$$\lambda_b = 60 v t_b d_b \frac{W^{1/2}}{d_b} = n W^{1/2} \quad (4)$$

ESTIMATING BEARING FAILURE RISK

Reliability analysis[13,14] is a convenient technique for determining the life expectancy of devices that ultimately fail as a result of wear or fatigue. Reliability is the probability of survival for a specified period of time under acceptable operating conditions. The mathematical expression for reliability is

$$P_s = e^{-\int_0^{\lambda} h d\lambda} \quad (5)$$

where

$$h = \frac{1}{n_b} \frac{dn_f}{d\lambda} \quad (6)$$

Risk is the probability of failure; its mathematical definition is

$$P_f = 1 - P_s \quad (7)$$

Both risk and reliability are dimensionless quantities between zero and unity.

Eight sets of performance data involving five bit sizes were assembled to illustrate applications of reliability analysis to rock-bit bearings. All bits in these samples were produced by a single manufacturer. Table 1 summarizes the performance data, and Fig. 4 shows the ranges of service and corresponding quantities of bearing failures. For bits equipped with O-ring seals, the life parameter is the number of bit revolutions. For those with metal seals, the life parameter is $nW^{1/2}$.

Application of Eqs. 5 through 7 to the performance data produced the results shown in Figs. 5 through 8, where the dashed lines designate regions of questionable accuracy because of sample size. Fig. 5 displays the bearing reliabilities of the bits with O-ring seals as functions of bit revolutions, and Fig. 6 uses the same life measure to compare the reliabilities of 7-7/8- and 12-1/4-in. bits equipped with metal seals. Because O-rings and metal seals show essentially the same level of reliability in 7-7/8-in. bits, bearings, rather than seals, are the likely cause of failure in both 7-7/8-in. bit samples. Comparison of the 12-1/4-in. bit samples, however, shows significant improvement in reliability with the metal seal. Improvement with the metal seal can also be shown by a similar comparison of the 9-7/8-in. bit samples.

Fig. 7 shows the reliabilities of all bit samples with metal seals as functions of $nW^{1/2}$. Rather than predicting the same reliability regardless of size (as forecasted by the derivation of Eq. 4), the curves form one family covering 14-3/4- and 17-1/2-in. bits and a second family covering 7-7/8- through 12-1/4-in. bits. The disparity between these families may indicate that Eq. 2 is not applicable, but it could also be the result of other factors. For example, it is suspected that many of the 14-3/4- and 17-1/2-in. bits experienced operating conditions that promoted accelerated wear of their cutter retention means. In addition to reaming, off-center bit rotation, steering forces imposed during directional work, and some forms of cutting-structure breakdown can cause such wear. Differences in application and the small size of the 9-7/8-in. bit sample could also be responsible for the variance within the family of smaller bits. Some of the 7-7/8-in. bits showed evidence of bearing damage resulting from cutting-structure breakdown. Fig. 8 was prepared by combining the members of each family to form single samples.

For analytical purposes it is often more convenient to use equations rather than graphs. For the interval, $0 \leq P_f \leq 1$, each of the curves in Figs. 5 through 8 can be represented by expressions of the form

$$P_f = a_1(\lambda - a_2)^{a_3} \tag{8}$$

For O-ring seals, the entire family of curves shown in Fig. 5 can be represented by the expression

$$P_{fo} = \frac{d_b^{3.63}\,(n - 10^5)^{1.72}}{4.74 \times 10^{13}} \tag{9}$$

Table 2 lists values of a_1, a_2, and a_3 for the curves in Figs. 7 and 8.

Use of these empirical equations outside the ranges of operation listed in Table 1 or for other bit types is not recommended.

The empirical equations for risk and their corresponding graphs provide an estimate of bearing life expectancy at the time a bit is placed in service. As a bit approaches an estimated life during actual use, its probability of achieving the estimated life improves and the risk of failure diminishes. When an estimated life is actually achieved without bearing failure, the probability of doing so becomes unity and the risk of failure becomes zero. To determine the reliability of a used bit, it is necessary to derive a new reliability function represented by the portion of the original reliability function beyond the life that has been achieved with new reliability and risk scales extending linearly to unity at the achieved life. Fig. 9 illustrates this construction. The corresponding mathematical expressions for reliability and risk are

$$P_{su} = \frac{P_{s2}}{P_{s1}} \tag{10}$$

$$P_{fu} = \frac{P_{f2} - P_{f1}}{1 - P_{f1}} \tag{11}$$

The following example illustrates the use of Eq. 11. Consider a 12-1/4-in. O-ring sealed bit that is to be run at 100 rev/min with the risk of bearing failure limited to 0.1. Application of Eq. 9, with $P_{fo} = 0.1$ and d_b = 12-1/4-in., yields a 0.9 probability of reaching 220,085 bit revolutions. This is equivalent to about 37 hours at 100 rev/min. Now, assume the bit was used for 37 hours but the penetration rate was slower than expected and it is desirable to run the bit longer to reach the casing point before making a trip. To achieve this additional footage, also assume that the risk of bearing failure will not exceed 0.05. Because the present bit life corresponds to an original risk of 0.1 and the new risk cannot exceed 0.05, $P_{f1} = 0.1$, $P_{fu} = 0.05$, and Eq. 11 yields $P_{f2} = 0.145$. This risk value is then used in Eq. 9 to obtain a new total life expectancy of 249,042 bit revolutions, which corresponds to 41.5 hours at 100 rev/min. Because the bit was already used for 37 hours, it can be run for 4.5 additional hours with only a 0.05 risk of bearing failure. Had the estimated time to casing point at 100 rev/min been 10 hours, Eq. 9 could have been solved with n = 282,000 bit revolutions to obtain $P_{f2} = 0.20$. Then Eq. 11 yields $P_{fu} = 0.111$ — i.e., the risk of failure for 10 hours of additional drilling at 100 rev/min is 0.111.

RELATING DRILLING COST TO RISK

One form of the drilling cost equation is

$$C_f = \frac{C_r}{R}\left[1 + \left(\frac{C_b}{C_r} + t_t\right)\frac{1}{t_b}\right] \tag{12}$$

As bit life increases, the second term within the brackets of Eq. 12 becomes smaller and drilling cost is reduced. Also,

$$\frac{1}{t_b} = \frac{60\,v}{n} \tag{13}$$

Thus, the risk of bearing failure can be related to drilling cost by combining Eqs. 4, 8, 12, and 13 for bits with metal seals and Eqs. 9, 12, and 13 for those with O-ring seals. Figs. 10 and 11 show the resulting relationships between the reciprocal of bit life and risk. These plots make it apparent that most of the reductions in drilling cost associated with extended bit life can be realized without exceeding a risk level of 0.2.

APPLICATION OF RELIABILITY DATA DURING THE PLANNING AND EXECUTION OF DRILLING PROGRAMS

The performance and reliability data included in this report were assembled to demonstrate the methodology described and, as mentioned earlier, should not be considered directly applicable to other bit designs with comparable seals. It is hoped, however, that this report will encourage others to apply the technique. Computer software[15] is available for making the reliability analyses after sufficient performance data have been assembled. The accuracy of each analysis is determined by the quality of the data and the size of the sample. It is desirable to have as large a sample as possible, with operating practices covering the full range of anticipated use.

After the reliability analysis is made, it is convenient to construct worksheets like those shown in Figs. 12 and 13. The upper right portions of these worksheets duplicate parts of Figs. 10 and 11. The left portion is obtained from Eq. 13, and the lower right portion is the graphic equivalent of Eq. 11.

In Fig. 12, the graphic solution for the previously discussed 12-1/4-in. bit application is illustrated with dashed lines. Entering the chart at 0.1 risk (Point A), a vertical line is drawn to intersect the bit-size curve at Point B. From Point B, a horizontal line is drawn to intersect the curve for 100 rev/min (Point C), where a vertical line is drawn to obtain the estimated bit life of 37 hours at Point D. To establish how much longer the used bit can be run with the risk of failure reduced to 0.05, the vertical line between Points A and B is extended to the lowest diagonal line at Point E. A horizontal line is then drawn to intersect the diagonal line radiating from 0.05 on the risk scale (Point F). From Point F, another vertical line is drawn to intersect the bit-size curve at Point G, and from there the process of estimating bit life is repeated with a horizontal line to Point H and a vertical line to Point I, where bit life is 41.5 hours.

The reverse of the procedures illustrated in Fig. 12 is shown in Fig. 13 for a 12-1/4-in. bit with metal seals. The lines connecting Points J through M establish 0.08 as the risk associated with a planned run of 40 hours at 40,000 lbf and 150 rev/min. The remaining lines show a risk of approximately 0.15 for 20 hours of additional operation after 40 hours of service is achieved. To determine that risk, Lines LN, OP, and PQ are drawn first. A vertical line is then drawn from Point Q and a horizontal line is extended from Point N. The intersection of these lines at Point R establishes the risk, which is read from the scale at the lower right (as indicated by the diagonal line extending from Point R to Point S).

CONCLUSIONS

1. Reliability analysis is an effective analytical tool for establishing the life expectancy of rock-bit bearings.
2. Metal-face seals significantly increased bearing life in the 9-7/8- and 12-1/4-in. IADC 517 and 527 bits used in this study.
3. Although drilling cost declines as bit life increases, the potential savings become relatively small when the risk of bearing failure exceeds 0.1 to 0.2.

NOMENCLATURE

a_1, a_2, a_3 = constants used to curve-fit risk vs. life
C_b = bit cost
C_f = cost per interval drilled
C_r = fixed operating cost of rig per unit time
d_b = bit diameter, in.
h = hazard rate
λ = life parameter
λ_b = bearing-life parameter
λ_s = seal-life parameter
L = bearing length
n = number of bit revolutions
n_b = number of bits in service
n_f = number of bits with bearing failures
p_c = maximum bearing contact pressure
P_f = probability of failure (risk)
P_{fo} = probability of failure for O-ring sealed bearings
P_{fu} = probability of failure for a used bit
P_{f1}, P_{f2} = probability of failure after specific periods of use
P_s = probability of survival (reliability)
P_{su} = probability of survival for a used bit
P_{s1}, P_{s2} = probability of survival after specific periods of use
r_c = radius of cutter bearing
r_j = radius of bearing journal
R = penetration rate
t_b = rotating time on bit during bit run, hours

t_t = time of tripping operations required to change bit, hours

v = rotary speed, rev/min

W = WOB, lbf

SI METRIC CONVERSION FACTORS

ft × 3.048*	E − 01	= m
°F (°F−32)/1.8		= °C
in. × 2.54*	E + 00	= cm
lbf × 4.448222	E + 00	= N

*Conversion factor is exact.

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Table 1
Bit Performance Summary

BIT DESCRIPTION				WEIGHT ON BIT 1000 LBF		ROTARY SPEED RPM		HOURS		DEPTH DRILLED FEET		NO. BITS WITH BEARING FAILURES
SIZE INCHES	SEAL	IADC CODES	NUMBER OF BITS	RANGE	AVG	RANGE	AVG	RANGE	AVG	RANGE	AVG	
7-7/8	O-Ring	517 & 527	1369	2-90	37	40-165	80	4-256	94	30-6074	2364	254
7-7/8	Metal	517 & 527	54	2-58	35	50-180	83	13-289	113	132-8976	3353	25
9-7/8	O-Ring	517	118	6-65	35	10-180	89	18-169	66	1-7375	1015	25
9-7/8	Metal	517	16	20-45	36	50-135	102	13-331	85	96-5803	1128	3
12-1/4	O-Ring	517	90	5-87	38	50-125	89	32-104	61	229-1343	596	40
12-1/4	Metal	517 & 527	75	5-80	42	80-260	139	3-189	53	39-1956	764	15
14-3/4	Metal	517	28	20-65	48	50-145	99	7-195	61	193-2948	708	18
17-1/2	Metal	437 517 & 527	19	10-100	51	60-200	123	16-97	44	131-4200	1008	10

Table 2
Empirical Constants for Forecasting Risk
of Bearing Failure with Metal Seals

BIT SIZE (INCHES)	a_1	a_2	a_3
7-7/8	2.0175×10^{-13}	25×10^6	1.5352
9-7/8	3.2651×10^{-15}	25×10^6	1.7134
12-1/4	4.9432×10^{-16}	25×10^6	1.8369
14-3/4	2.1401×10^{-11}	20×10^6	1.3189
17-1/2	1.9446×10^{-11}	20×10^6	1.3276
7-7/8 - 12-1/4	3.8879×10^{-15}	25×10^6	1.7350
14-3/4 - 17-1/2	6.3408×10^{-12}	20×10^6	1.3880

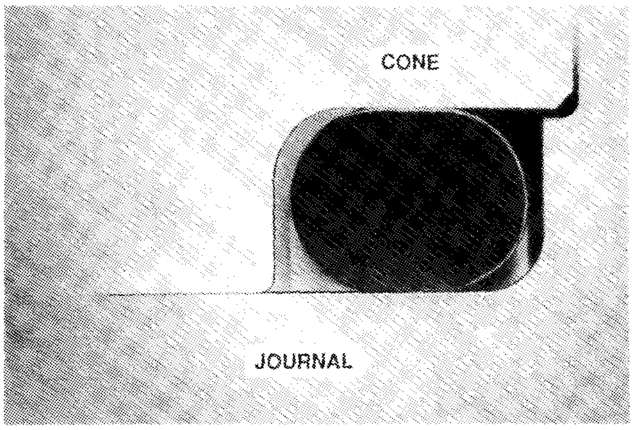

Figure 1 - O-ring seal

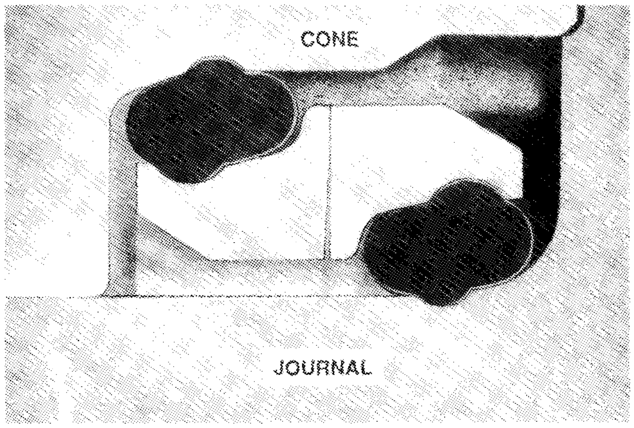

Figure 2 - Metal-face seal

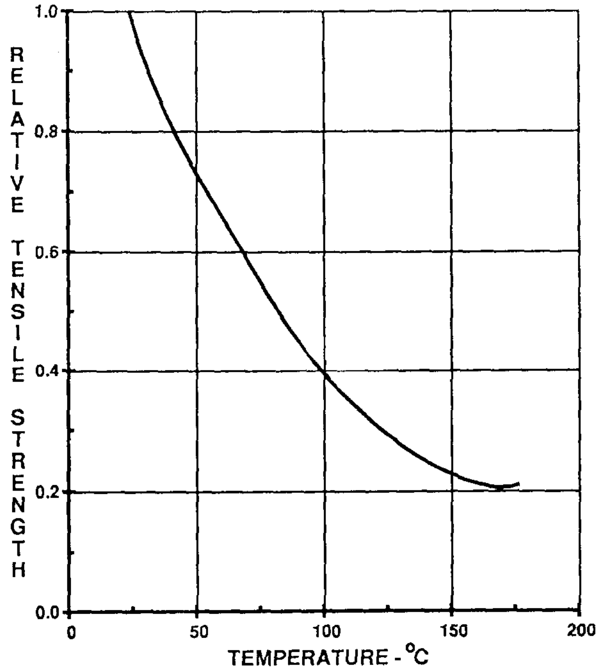

Figure 3 - Tensile strength vs. temperature for a typical rock bit O-ring seal

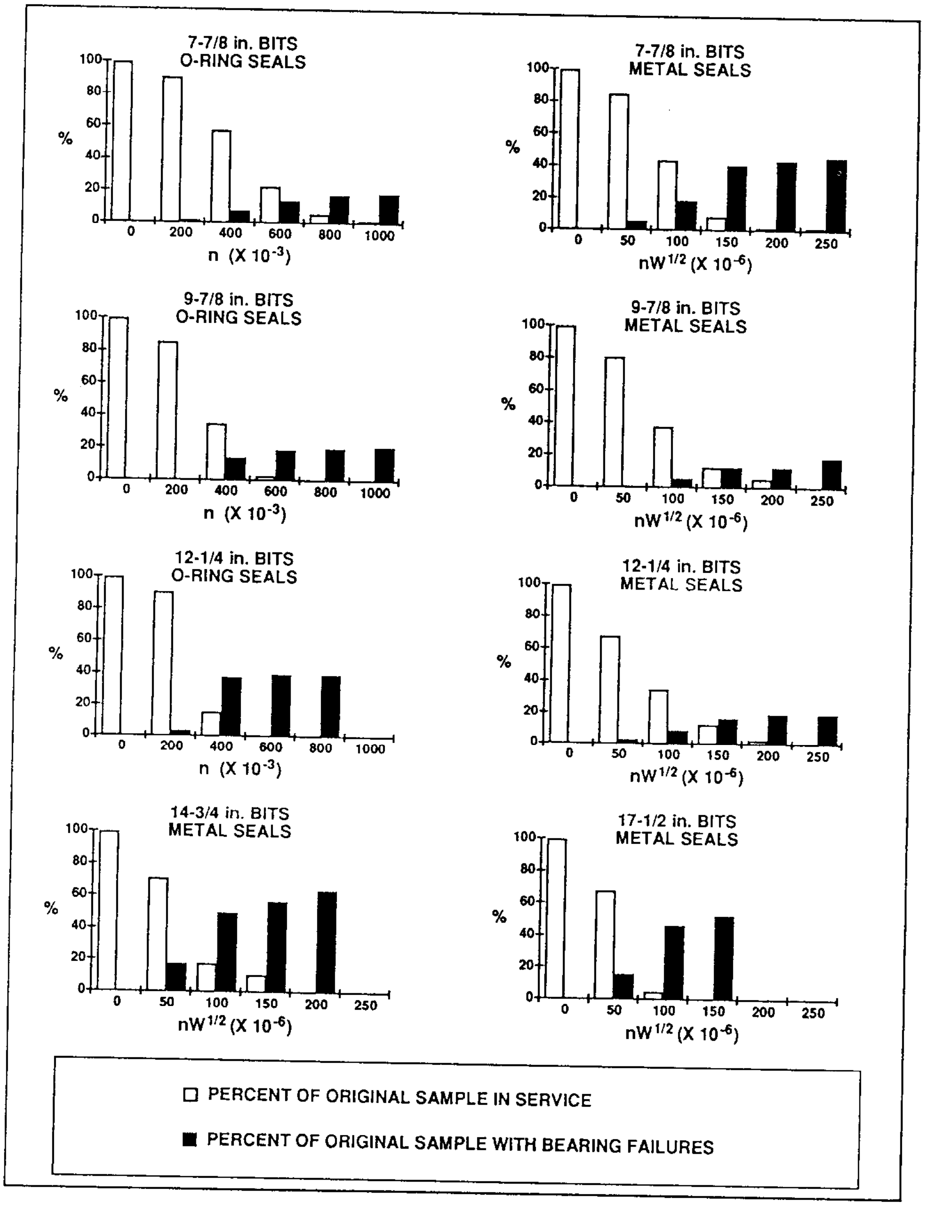

Figure 4 - Distributions of use and bearing failures for bit samples listed in Table 1

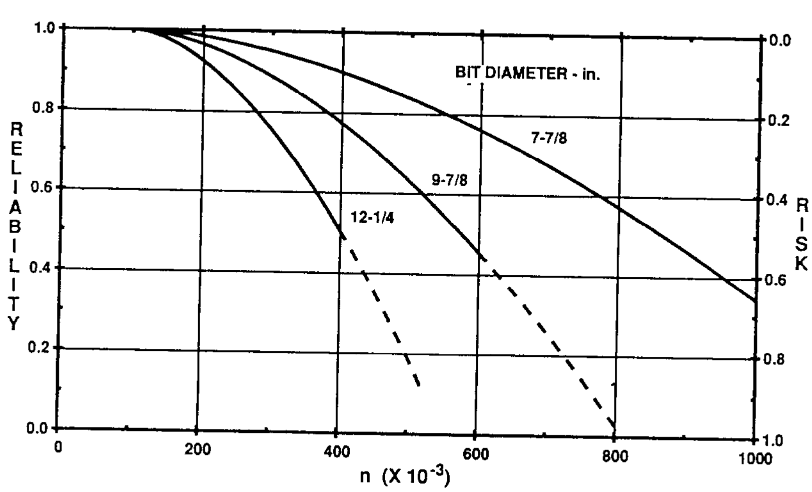

Figure 5 - Bearing reliability and risk of failure for bits with O-ring seals

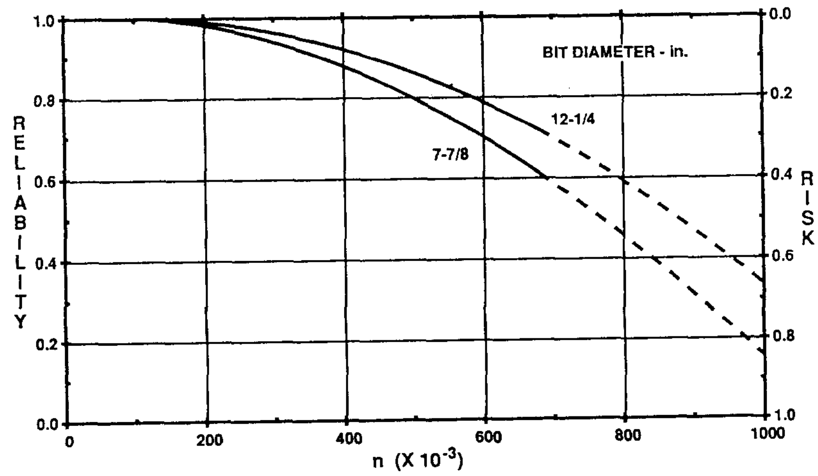

Figure 6 - Bearing reliability and risk of failure vs. bit revolutions for 7-7/8 and 12-1/4 in. bits with metal-face seals

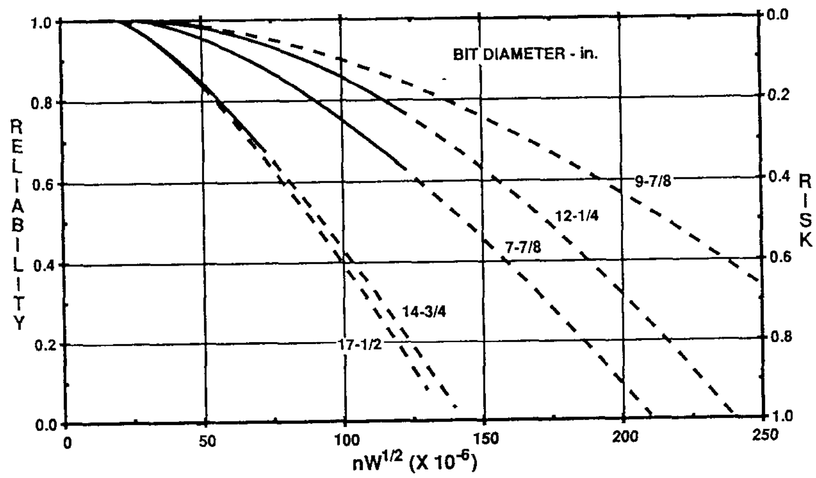

Figure 7 - Bearing reliability and risk of failure for bits with metal-face seals

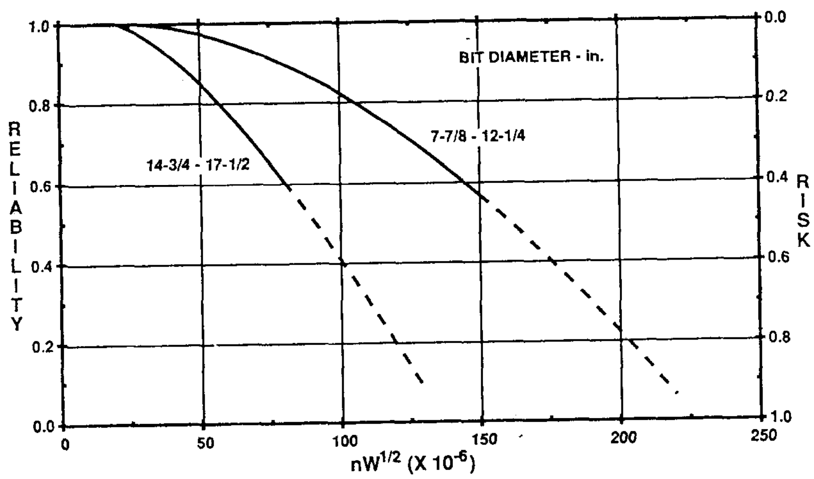

Figure 8 - Bearing reliability and risk of failures for two families of bits with metal-face seals

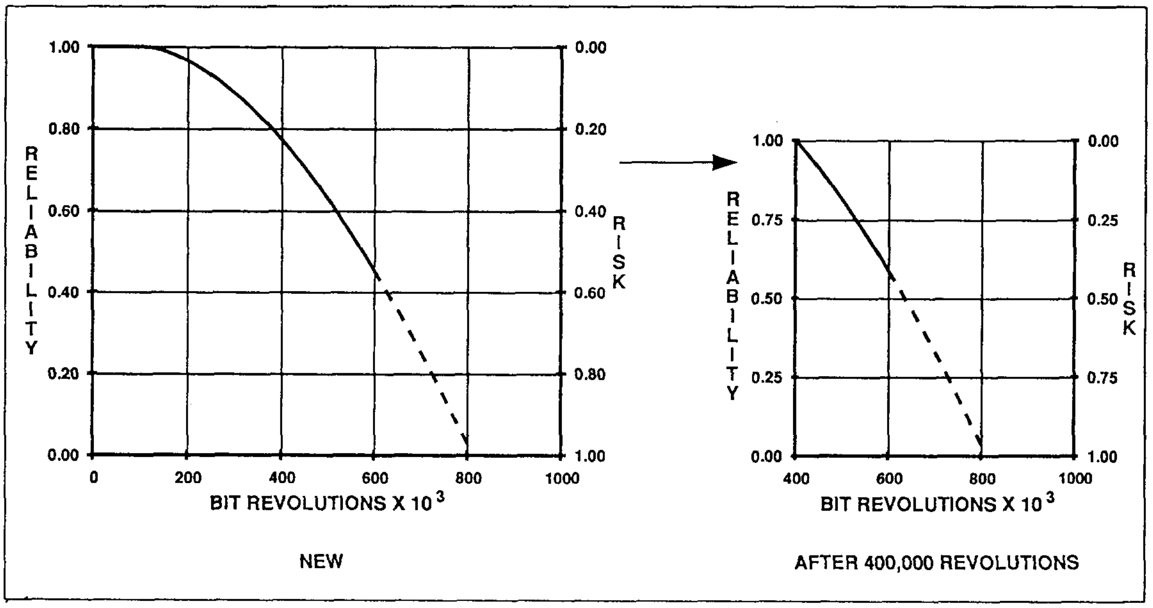

Figure 9 - Reliability of new and used 9-7/8 in. bits with O-ring seals

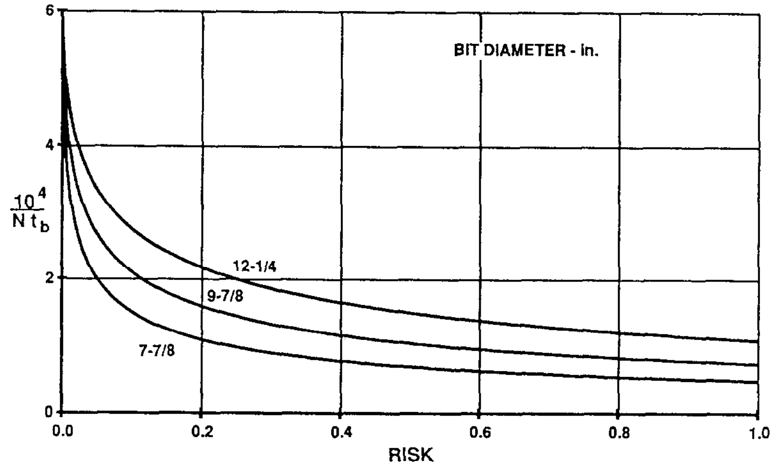

Figure 10 - Reciprocal of life vs. risk for bits with O-ring seals

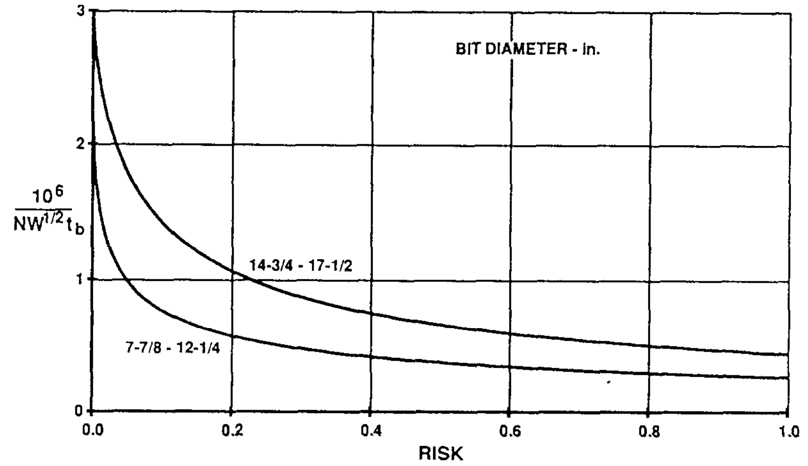

Figure 11 - Reciprocal of life vs. risk for bits with metal-face seals

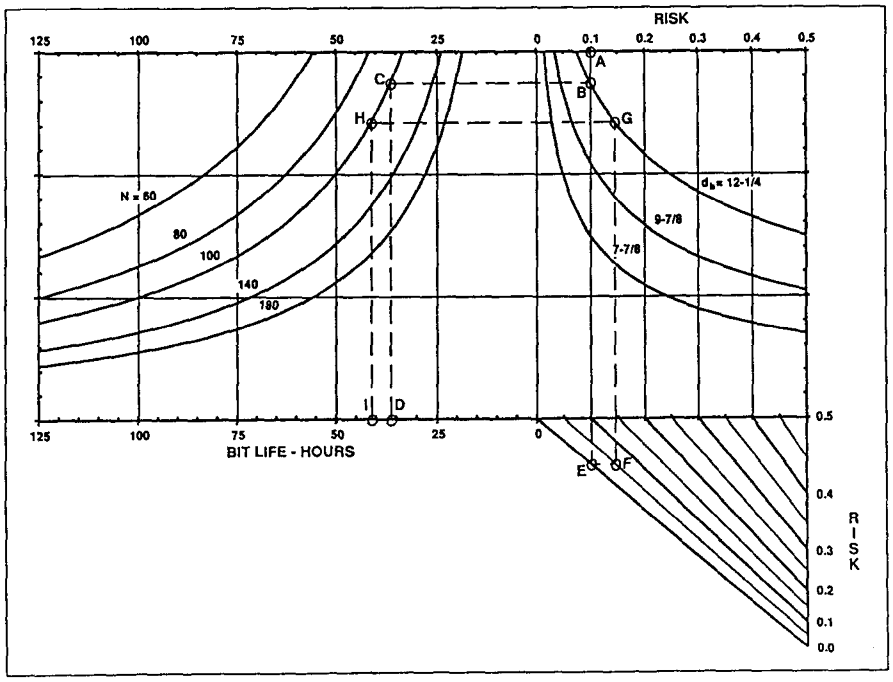

Figure 12 - Bearing life and risk forecast chart for bits with O-ring seals

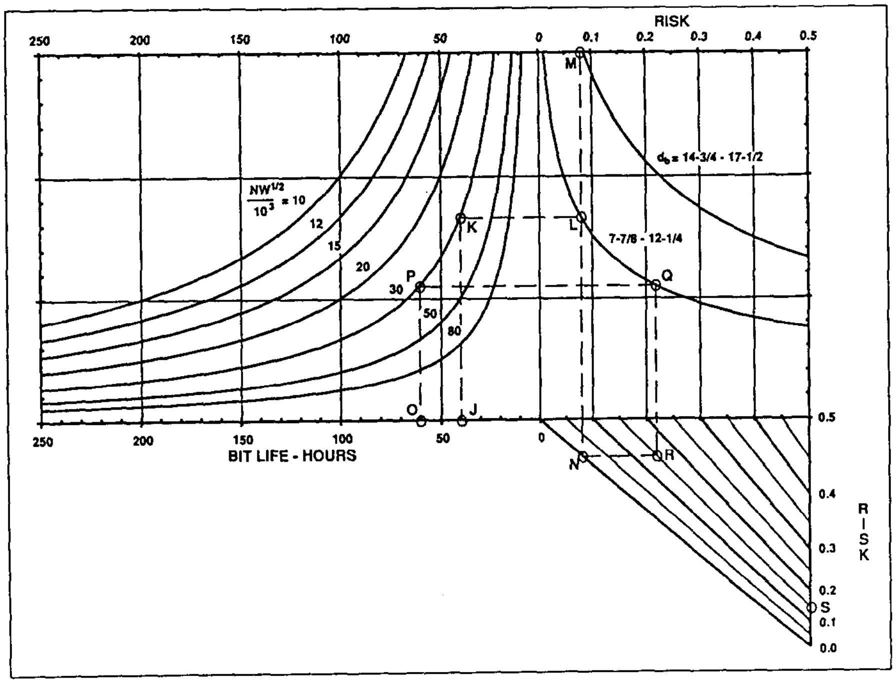

Figure 13 - Bearing life and risk forecast chart for bits with metal-face seals