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DESIGN RELIABILITY OF AUTOMOTIVE COMPONENTS

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Introduction

In the design of automotive components to resist fatigue a number of factors are used to account for surface finish, type of loading, mode of loading, size, etc. These factors have been experimentally determined for various materials and operating conditions. However, because of the inherent scatter in the engineering properties, each of these factors represents a mean value computed from the scatter of the observed data.

The performance of an automotive part in service is judged by the number of failures or time to failure of a small number of components rather than by the mean life. This, in turn depends on the degree of scatter. Thus in a meaningful design it is essential to incorporate a reliability factor which would provide for this scatter.

Reliability can be defined as the probability of a product performing a specified function, under given conditions, for a specified period of time, without failure. Thus, the function of the part, the operating conditions, and the time of operation are all important aspects of reliability.

In statistical terms reliability is the converse of the probability of failure. If the probability of failure is 1 the part will fail and, therefore, the reliability is zero. Similarly, if the probability of failure is zero the part will not fail and reliability is 1 or 100, if expressed in percent. Thus, 80% reliability means 20% failure, 95% reliability means 5% failure, etc.

Thus, reliability implies an avoidance of failure. In the case of automotive components this means principally fatigue failures as most automotive parts are subjected in service to repetitive loading.

The Problem of Scatter

It is the fundamental characteristic of manufactured parts that they exhibit variation in life when subjected to identical loading conditions. Aside from the variations resulting from the human error in testing, or from the limitations of the test equipment, the principal variation lies in the parts themselves. No two pieces produced are exactly the same, no matter how refined is the process. Although the differences may be small, they nevertheless exist.

This is illustrated[1] by the anti-friction bearing in truck front wheel spindles (Fig. 1). Although the rated life is 100,000 miles, 10% of the bearings may fail under 20,000 miles and another 10% will last over 200,000 miles.

All automotive parts show scatter, some to a greater degree than others. Engine exhaust valves, for example, exhibit considerable variation in life.[2] In Fig. 2 each group comprises a number of engines, all of the same design, which were tested in fleet operation. The life of a valve shown is an average between the first and the second valve that failed in a given engine. Similar tests conducted on the dynamometer (Fig. 3) under controlled conditions show about the same degree of scatter as in fleet operation. This suggests that scatter is an inherent characteristic of a fabricated part.

Faced with this problem of scatter it has been intuitively recognized that it will not suffice to evaluate an automotive part from a single sample and a recourse must be taken to an average (mean) of a number of samples. This has been a widely accepted method of evaluating data.

The use of the average alone has a serious drawback. Half of the specimens have a life lower than the average and, therefore, a design based on the mean value implies a 50% reliability, that is, half of the parts will fail. This would be an intolerable condition and the reason that 50% failures do not occur in actual practice is because in design calculations based on mean values generous factors of safety are provided.

This has been recognized for some time and efforts have been made, mostly on empirical basis, to focus attention on the low end of the scatter band. Figure 4 refers to considerable data accumulated on bevel and hypoid gears.[3] The recommended design line for maximum of 5% failures is obviously much more meaningful than the commonly used mean line which implies 50% failures. The only shortcoming of the method shown in Fig. 4 is that it necessitates collection of considerable amount of data, generally beyond the capacity of an average industrial laboratory.

This study was undertaken to provide a useful basis for design of automotive components which would provide for the inherent scatter in their lives.

The Log-Normal Distribution

Meaningful analysis of scatter data necessitates the use of statistical methods.[11,12,13] The dispersion, or scatter, is described by a numerical factor. The usual measure of standard deviation can be used in connection with a normal distribution of occurrences, or the log-standard deviation can be used with the log-normal distribution. More refined methods, such as the extreme value distribution, the probit method, or the staircase method of fitting a regression line to the distribution did not offer any higher accuracy in the present case.

For this study the log-normal distribution was used.[5,6]. The reason for using this distribution is that fatigue data plotted on a linear scale show a skewed distribution[4,5] (Fig. 5). The explanations for this are numerous. One of the most logical ones is that a limit of values exists at the lower end of the scale, as a part cannot have negative life or strength, while no limit exists at the upper end of the scale. Further, one very large value will have greater effect on the mean than will several small values. Thus, the mean tends to be above the peak value of occurrences.

Through the use of logarithms, a skewed distribution of values can be transformed into a close approximation of a normal distribution. The statistical methods applicable to a normal distribution are much simpler, are readily applied and are as meaningful as other statistical methods. For this reason, all statistical operations have been performed with the logarithms of life. Several checks performed with the present data confirmed that the resulting distributions were nearly normal.

Figure 6 shows one such check. Line A is a plot of bevel gear data based on a log-normal distribution of fatigue life of bevel gears. This method, discussed later in the report in greater detail involves the conversion of life N to log N and then finding $\overline{\log N}$ (which is mean log N) and log N (standard deviation of log N) and plotting the ratio of $N/\overline{N}$ (right hand ordinate in Fig. 6) for different levels of reliability (upper abscissa).

Line C is a plot of the life test data on a logarithmic probability paper. This method is based on the fact that the cumulative distribution function of any log-normal distribution will plot out as a straight line on the logarithmic probability paper. Hence we can tabulate our data in the order of failure and assign them rank $R = m/n+1$, where m is the ranked order of a given specimen from a total of n specimens in a sample. That is, if we have specimens whose lives are N_1, N_2, N_m .... N_n we assign them ranks $1/n+1$, $2/n+1$ .... $m/n+1$, ... $n/n+1$ respectively.

These ranks are then plotted on the Percent Failures (lower abscissa) and the lives on the life-cycles (left hand ordinate) and we plot these on the logarithmic probability paper. Next we fit the best straight line to this plot (by least square method). If the distribution of the data were log-normal we would get a straight line on this paper. This is the case as evidenced by Line C. Now if we wish to plot the ratio of $N/\overline{N}$ for different reliabilities, all that is necessary is to draw a line through 50% probability, parallel to line C. This produces line B which is quite compatible with the calculated line A.

The statistical analysis of fatigue data can be handled in two ways. A distribution of stresses at a fixed life can be found, or a distribution of life at a particular stress. In the first phase of this study the distribution of life values at a given stress was considered. Most of the test data obtained on automotive parts was available in this form. Generally, the load or stress was set and the parts were run to failure. The number of cycles was then recorded for each part and the scatter observed. This may have been repeated at a different stress level or at several levels.

The most common measure of dispersion of occurrences is the standard deviation. The most important property of this parameter is that 68.23% of the occurrences in the normal distribution are contained within the range of one standard deviation above and below the mean value; 95.45% within ± 2 standard deviations; and 99.73% within ± 3 standard deviations.

This property is especially useful for the purpose of finding a scatter factor, as the maximum percentage of failure can be readily expressed as a certain number of standard deviations from the mean. Furthermore, because the number of occurrences outside of a particular standard deviation range includes, both parts of very long life and parts with short life, a range of three standard deviations is equivalent to a failure level of .135%, or a reliability level of 99.865%; two standard deviations 2.28% failures, or 97.72% reliability level; 1.645 σ gives 5% failures or 95% reliability; 1.282 σ gives 10% failures or 90% reliability; 1 σ 16% failures and 84% probability; and .675 σ gives 25% failures and 75% reliability level.

Standard deviation in the log-normal distribution can be calculated from the following expression:[5]

$$\sigma_s = \left(\frac{\Sigma (\log N)^2}{n} - (\overline{\log N})^2 \right)^{\frac{1}{2}}$$

where

σ_s = standard deviation (actually the "best estimate" of the population variance)

$\overline{\log N}$ = mean value of the logarithms of the life values to the base 10

$\Sigma (\log N)^2$ = summation of the squares of the logarithms of the life values

n = number of specimens in sample

Knowing $\overline{\log N}$ and K σ (where K is the desired multiple of σ) by subtracting K σ from $\overline{\log N}$, the log of life corresponding to a given reliability is obtained. By taking the anti-log of this life and dividing it by the mean life (50% reliability) the Design Life Factor is derived. This factor is thus life at a given probability divided by life at 50% probability and it is plotted against percent reliability on a log-probability paper. Figures 7-15 constitute these plots for various cases.

Reliability of Automotive Components

In this manner, considerable data obtained over a period of years, and also some found in literature was analyzed in the manner indicated above and plotted as shown in Figures 7-15. In these graphs the upper and lower abscissas represent percent reliability and percent failures respectively. The ordinate gives Design Life Factors. The original data, from which these calculations were made were expressed as life in cycles, hours, miles, etc. A low design factor means high scatter and a high factor considerable uniformity in the life of the parts tested.

The stress or load levels corresponding to the above lives were the design stresses under which these parts were tested. In most cases these were located somewhat below the midpoint between the ultimate tensile strength and the endurance limit of the material. In those cases were lives were available at several stress levels the information was so noted and further analyzed.

The Design Life Factors

The analysis of Figs. 7-13 suggests the following. Because of manufacturing variations one would expect more scatter in actual automotive parts than in laboratory specimens. This was found to be approximately the case, as shown in Fig. 14. Within the manufactured parts themselves (Figs. 7-11), those parts which are subjected in service to contact loading (ball bearings, hypoid and bevel gears, engine valves) were found to have lower life factor than parts under flexural loading (crankshafts, springs, fans, etc.) Fig. 15. Note that the transmission helical gears had a relatively high life factor (Fig. 7). In this case the critical load was flexural as all the failures occurred at the root of the tooth.

The wide scatter of members under contact loading has been generally recognized.[7] In the case of ball bearings life is inversely proportional to the ninth power of the unit pressure, so that even a sligth variation in the bearing geometry or in the applied load may produce considerable variation in life.

Finally, no particular interrelationship can be expected within the various automotive components (Fig. 7-11). The scatter in life and thus the value of the design life factor at any reliability level depends on many things: the complexity of design at the critical section, uniformity of material properties, method of manufacture, quality of the inspection methods, etc. and these will differ among the various automotive parts. Thus a shaft whose critical section is a keyway would be expected to show higher variability in life than a shaft whose critical section is a large fillet. The size and the method of grinding the fillet can be carefully controlled and therefore, the shaft should show a relatively good uniformity in life. On the other hand it is more difficult to control the manufacture of a keyway and more scatter can be expected. Thus, in Fig. 7 higher design life factor was obtained for a cast wheel, where in the region of maximum stress there was no abrupt changes in section than in wheel spindles which had an 1/8" fillet radius.

For design purposes 95% reliability may be used in design calculations of parts whose failure can be regarded principally as an economic loss but not a loss of life of vehicle occupants. Into the first category belong body, engine, transmission, and some drive line components. For the latter (steering and suspension parts) a 99.9% reliability should be used instead. The information in Figs. 7-11 is tabulated under the two headings in Table 1.

The Design Stress Factors

For design purposes some problems are best solved in terms of the life at a given stress, while others in terms of stress at a given life. Figures 7-13 and Table 1 provide the information for the former. That is, at any required level of reliability the design life as a fraction of the mean life can be determined. In this manner, the average life of automotive components, conventionally obtained from laboratory tests, can be translated into a more meaningful design life where reliability and thus the maximum percentof failure can be stated.

The other category of design problems calls for the solution of stresses at a given life. To do this it is first necessary to establish the variation in the life scatter with the stress level. A casual review of literature[8,9,10] indicates that in some cases scatter is independent of stress, while in other cases it may either slightly or pronouncedly increase or decrease with the stress level (Figs. 16-18). The same was found to be true in the present case.

It is significant to note (Figs. 12 and 13) that in the case of materials magnetically sorted for permeability and tested in torsion the design life factor: 1) is largely independent of stress: 2) it is much higher for any level of reliability than materials not sorted. This reflects the uniformity of samples obtained. The benefit of this uniformity to the service life of automotive components is worth noting.

In Figs. 19 and 20, by dividing at a given life, the stress at 99.86% reliability (3 standard deviations) by the stress at 50% reliability (mean stress) a Design Stress Factor $S_{99.86}/S_{50}$ was obtained. This was repeated for various materials, with results as shown in Fig. 21. It will be noted that for the softer materials studied, in order to assure ourselves of 99.86% reliability, that is less than 15 failures in 10,000 pieces, it is necessary to design the part to approximately 80% of the average value of the fatigue strength.

For the 4340 steel the percent reduction in the fatigue strength will be considerably greater. Thus, for a life of 500,000 cycles the design should be based on approximately 50% of the mean fatigue strength found in handbooks for this particular life.

Similar study was made for ball bearings, with the results shown in Fig. 23 which was derived from Fig. 22. The design stress here should be 80% of the mean fatigue strength.

The above analysis was concerned with the finite life regions (sloping lines) of the stress-life relationships. Calculations were also made for the endurance limit regions of several automotive components. Here, however, the data were less well defined. In some cases the distribution was found to be normal, in other cases log-normal, and in a few cases not at all defined.

Design Life Factors

Automotive Parts

	Reliability	
	95%	99.9%
Wheel	.66	.45
Leaf Spring	.60	.38
Fan	.57	.35
Transmission Gear	.49	.26
Crankshaft - Design A	.46	.22
Crankshaft - Design B	.40	.18
Front Wheel Spindle	.33	.13
Engine Exhaust Valve	.20	.05
Hypoid Gear, 93 KSI	.33	.13
Hypoid Gear, 105 KSI	.37	.16
Bevel Gear, 75 KSI	.32	.11
Bevel Gear, 93 KSI	.27	.084
Ball Bearing, 388 KSI	.34	.13
Ball Bearing, 430 KSI	.26	.08
Ball Bearing, 475 KSI	.30	.11
Ball Bearing, 510 KSI	.34	.14
Ball Bearing, 540 KSI	.24	.07
Axle Shaft, Automobile, 27 KSI	.35	.14
Axle Shaft, Automobile, 38 KSI	.46	.24
Axle Shaft, Automobile, Shot Peened	.37	.16
Axle Shaft, Farm Tractor, 30 KSI	.57	.34
Axle Shaft, Farm Tractor, 54 KSI	.52	.29
Roller Chain, 650 lb	.35	.14
Roller Chain, 800 lb	.32	.12

Table 1

Appendix

Some additional information on the characteristics of the automotive components studied:

Ball Bearings: 1/2" radial, SAE 52100. Also see reference 15

Bevel and Hypoid Gears: See reference 3

Wheels: Truck, malleable iron

Leaf Springs: Truck, SAE 4068, 444-477 BHN

Gears: Truck, Transmission Helical, SAE 8620, carburized, 58-63R_c

Crankshaft: Automobile, SAE 1046, 228-269 BHN

Front Wheel Spindles: Automobile, SAE 1046, 248-293 BHN

Engine Valves: Truck, Exhaust Valves

Axle Shafts: Farm Tractor, SAE 8635, 269-321 BHN

Axle Shafts: Automobile, SAE 8650, 388-444 BHN, Also see reference 14

Roller Chains: American Standard No. 40

Fan: Automobile, 6 blade spider type, SAE 1020

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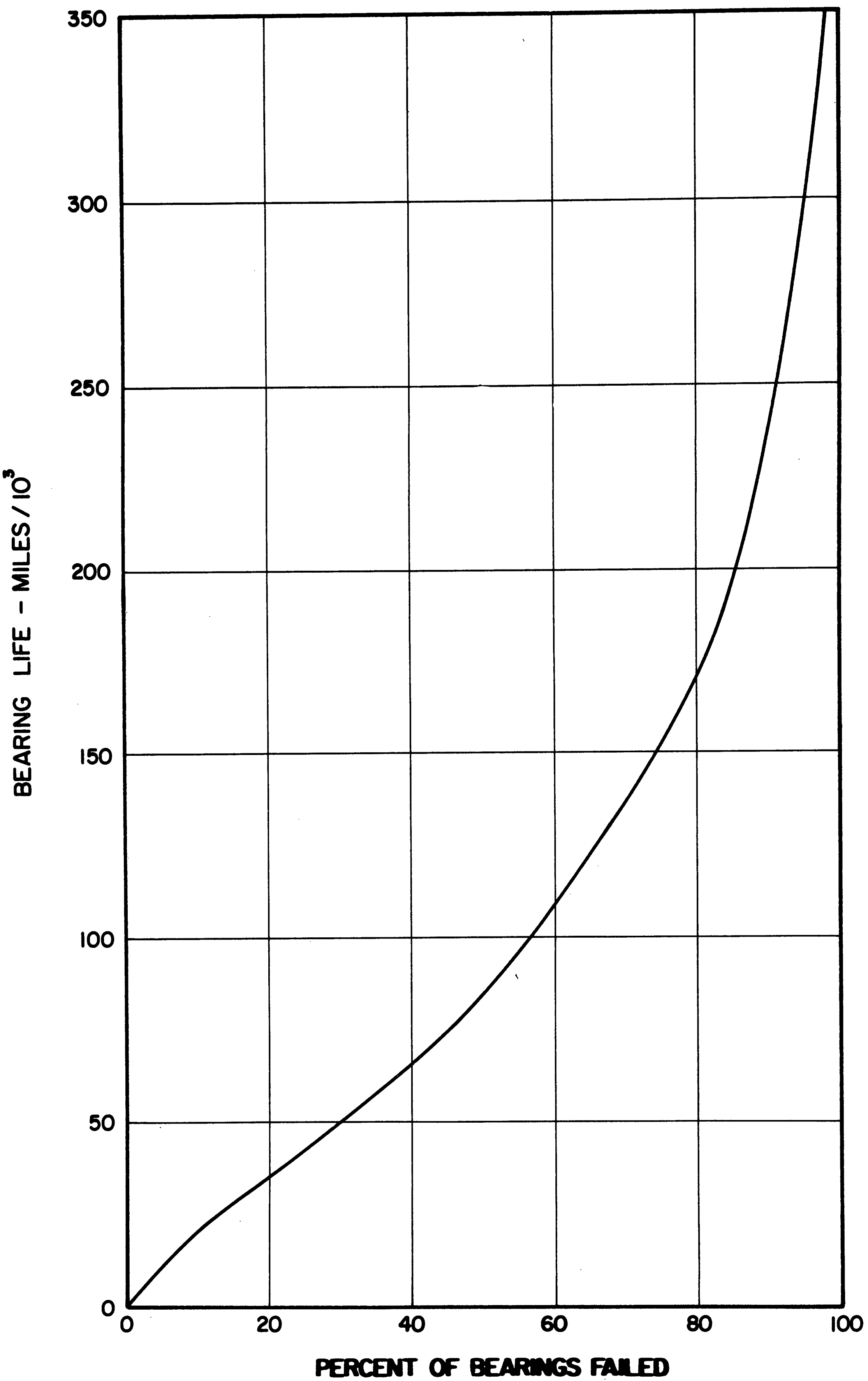

Figure 1. Life Expectancy of Ball Bearings.

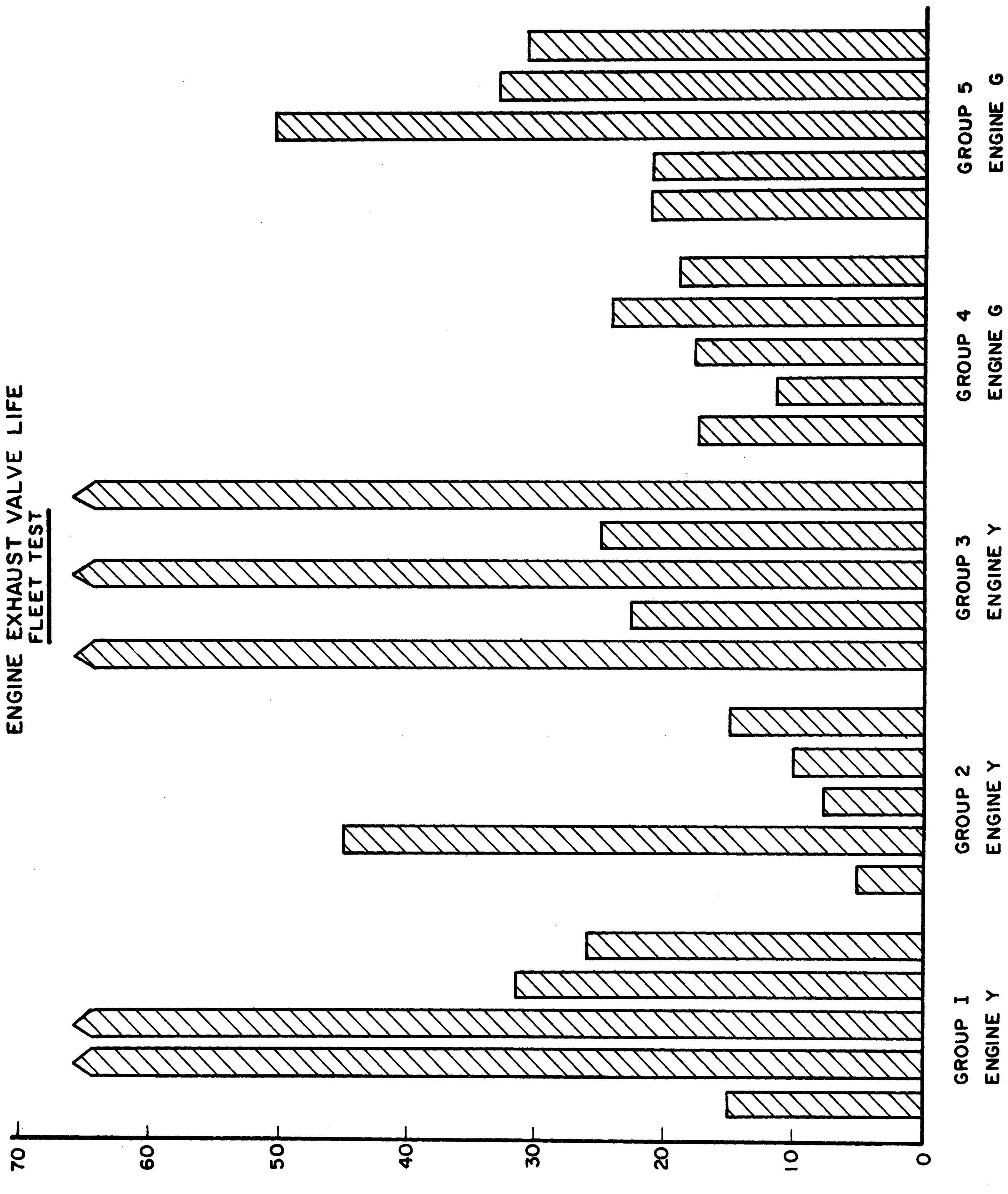

Figure 2. Scatter in Life of Engine Exhaust Valves - Fleet Test[2].

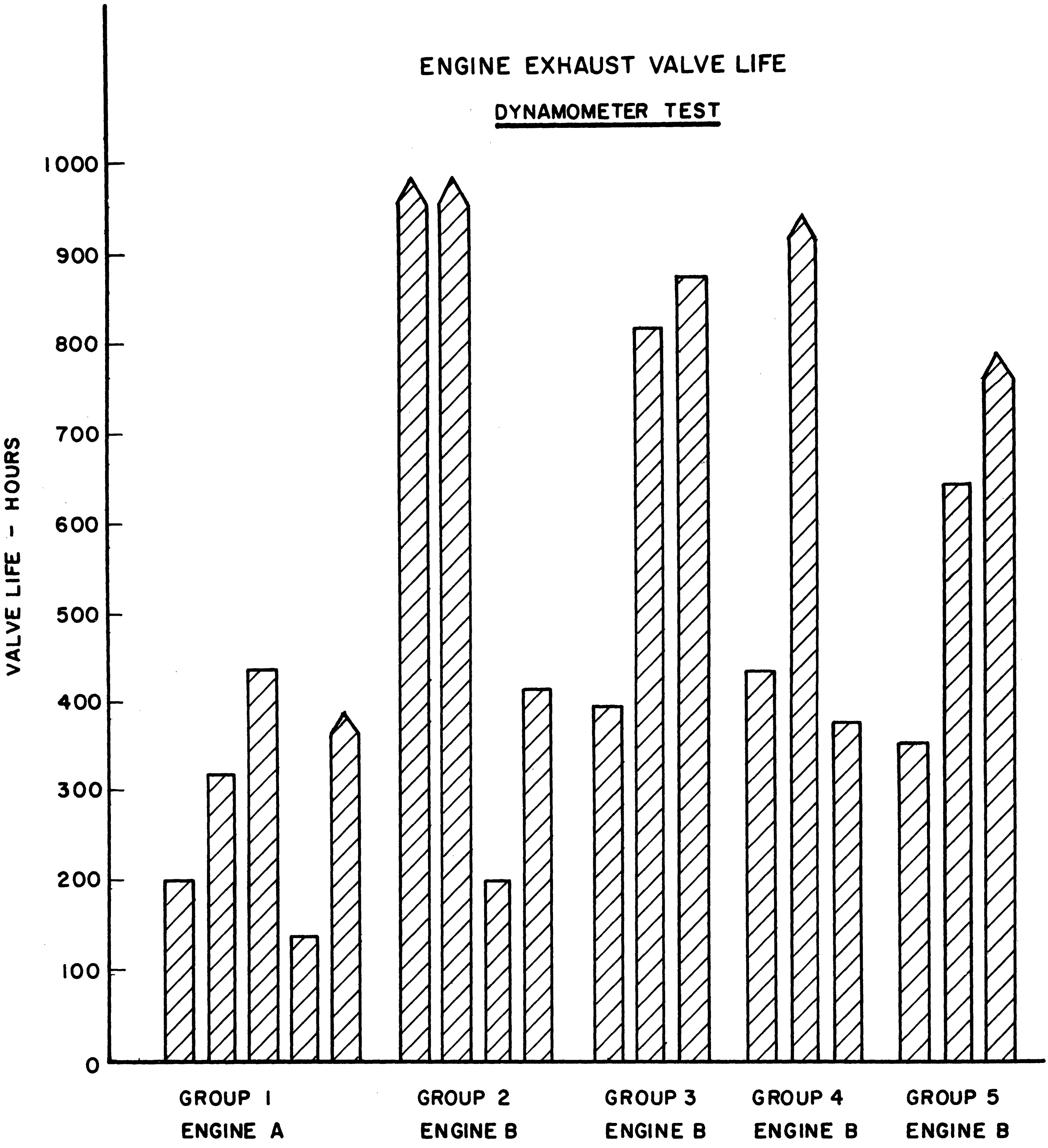

Figure 3. Scatter in Life of Engine Exhaust Valves - Dynamometer Test[2].

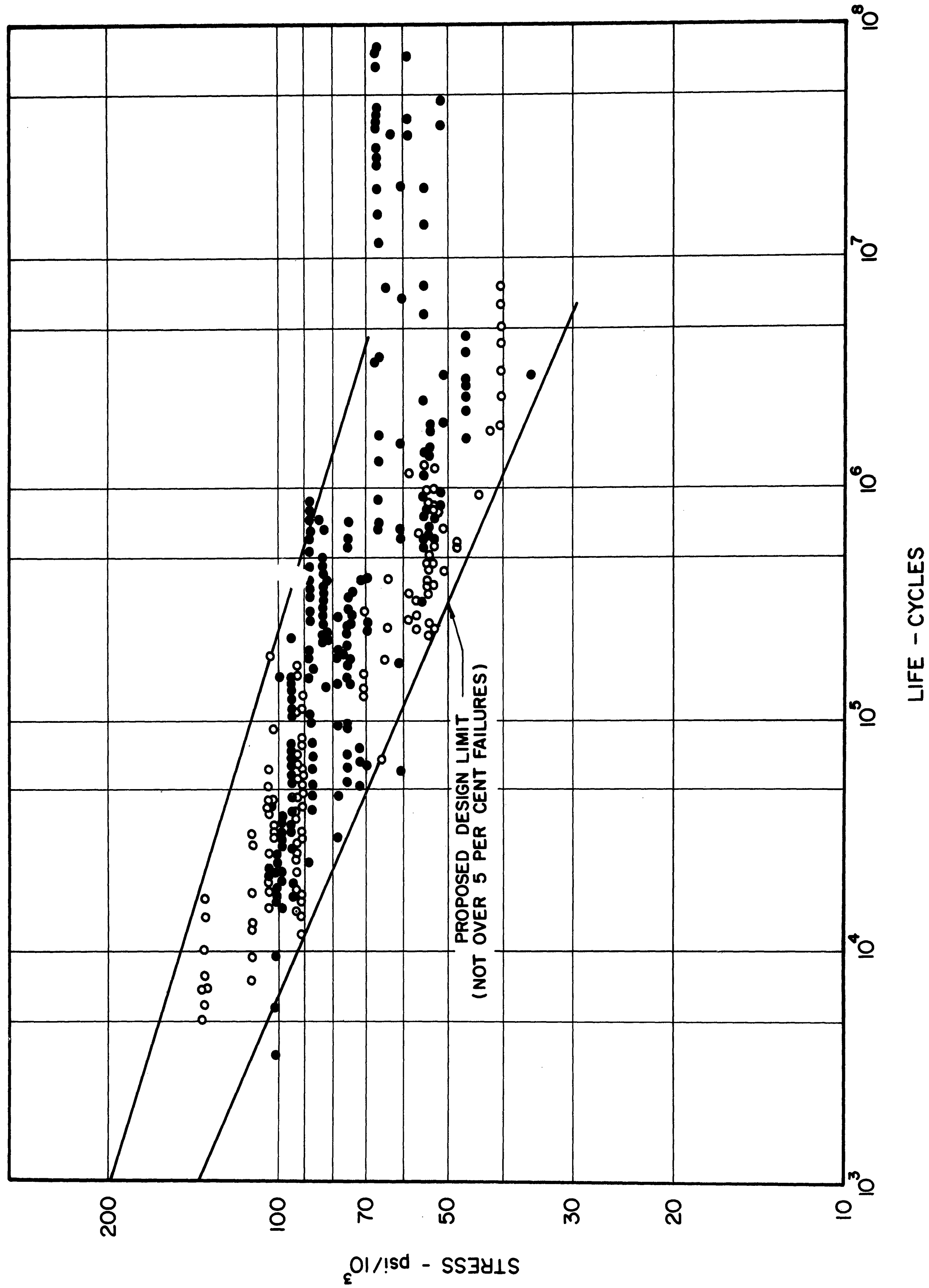

Figure 4. **Scatter** in Life of Gears-Bevel: Solid Circles; **Hypoid**: **Open** Circles[3].

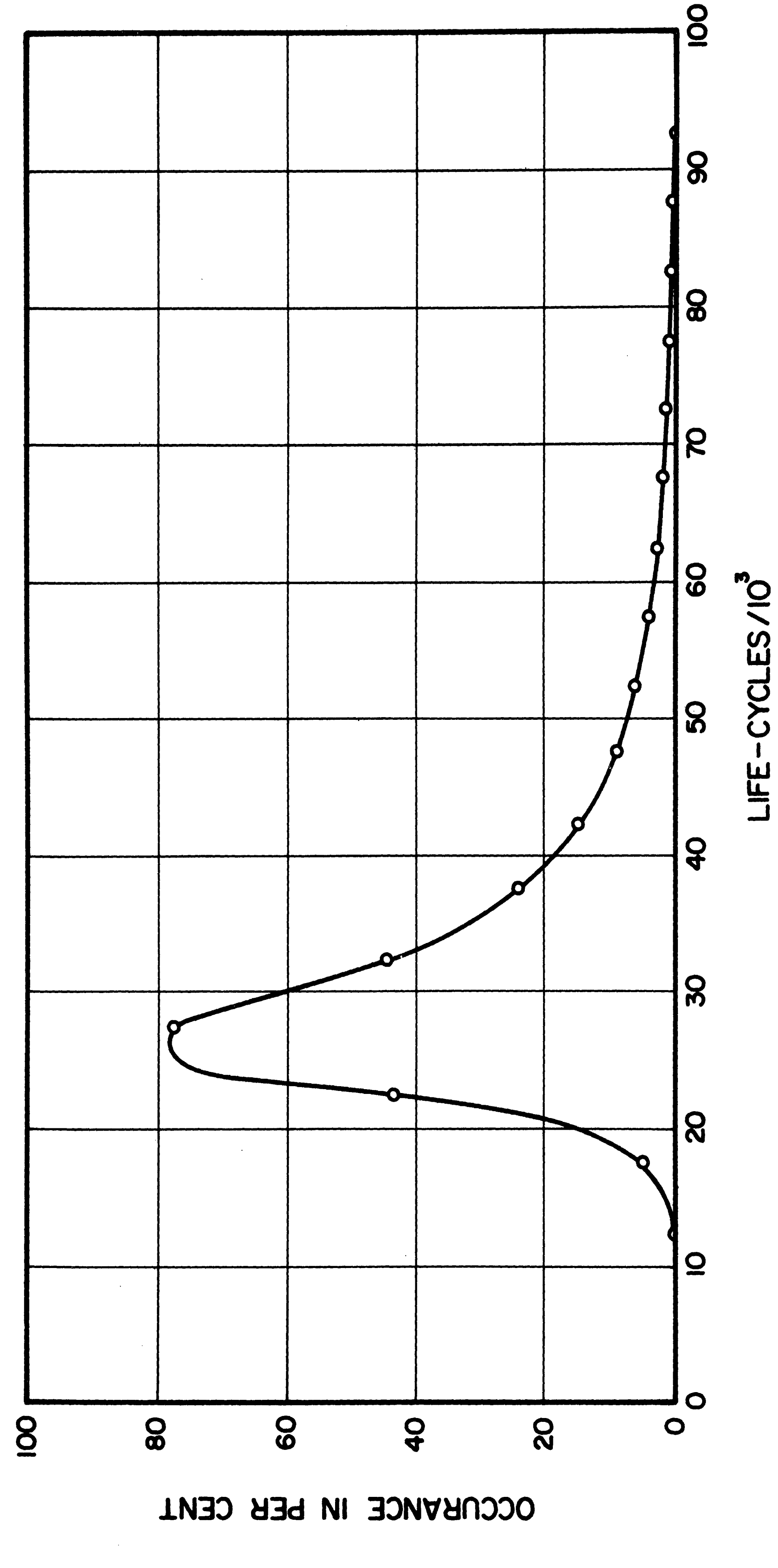

Figure 5. **Distribution of Fatigue Life** - 0.06% carbon steel, 50-57.5 KSI Tensile[4].

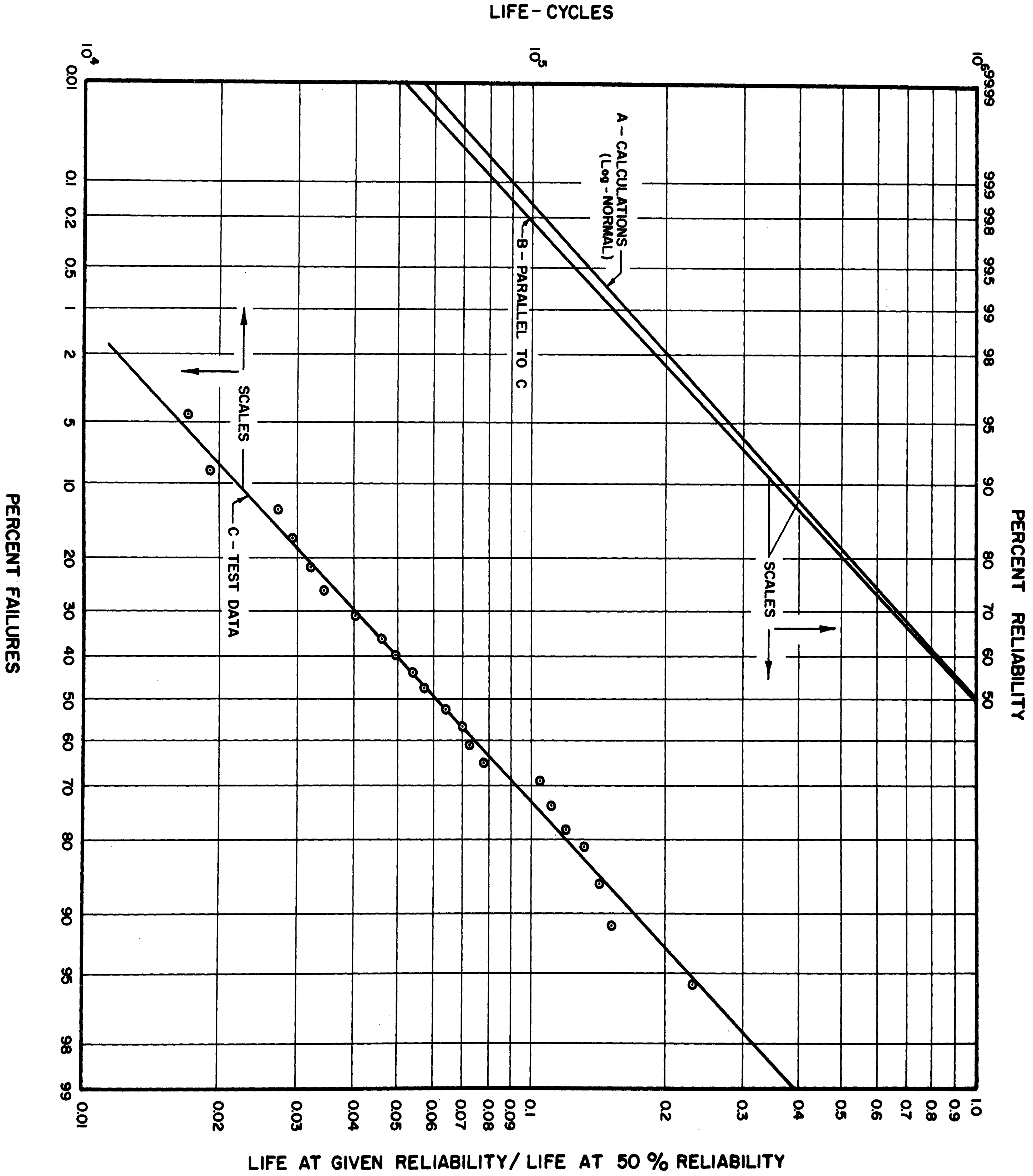

Figure 6. Experimental and Calculated Distributions of Bevel Gear Fatigue Life.

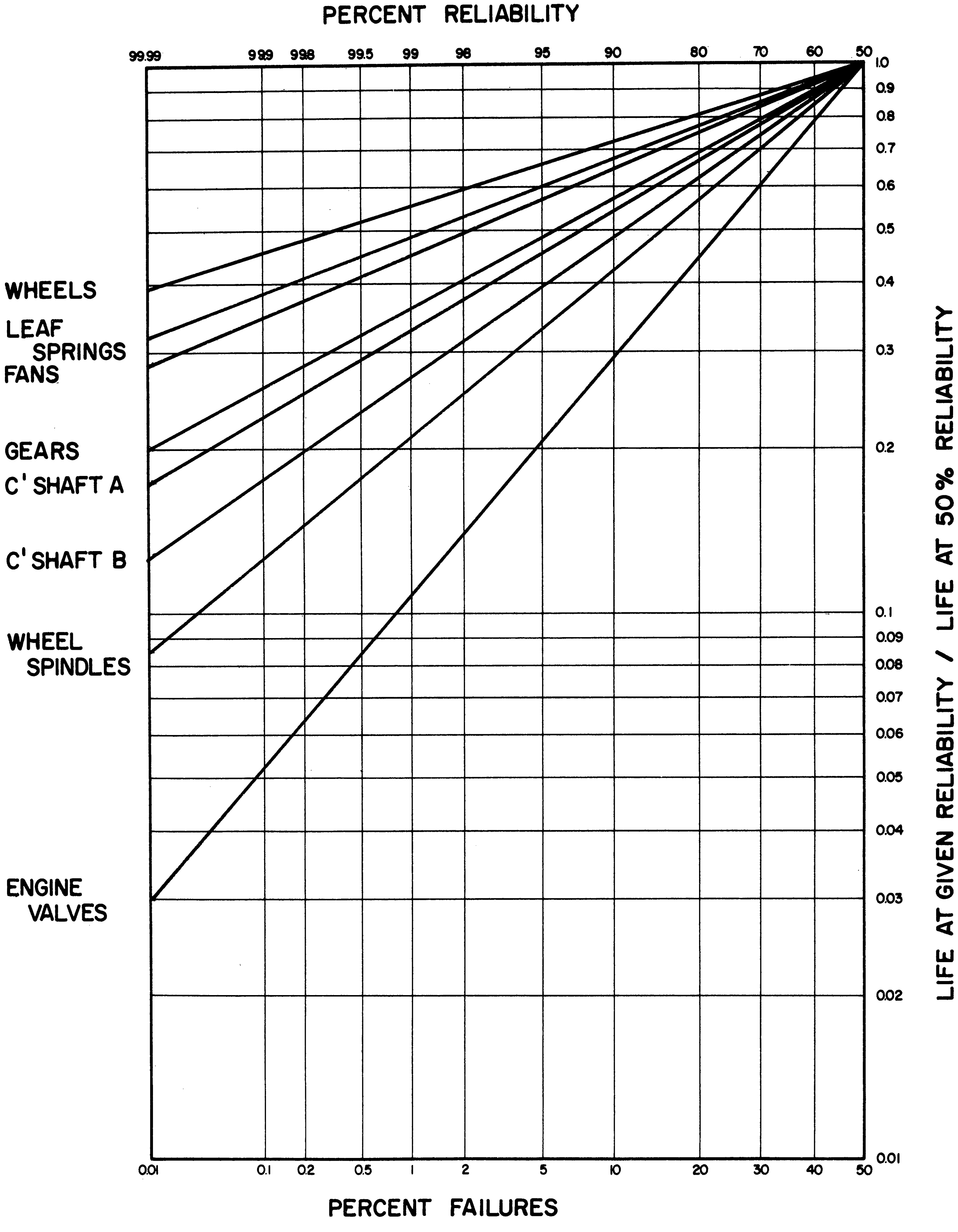

Figure 7. Design Life Factors at Different Reliabilities - Some Automotive Components.

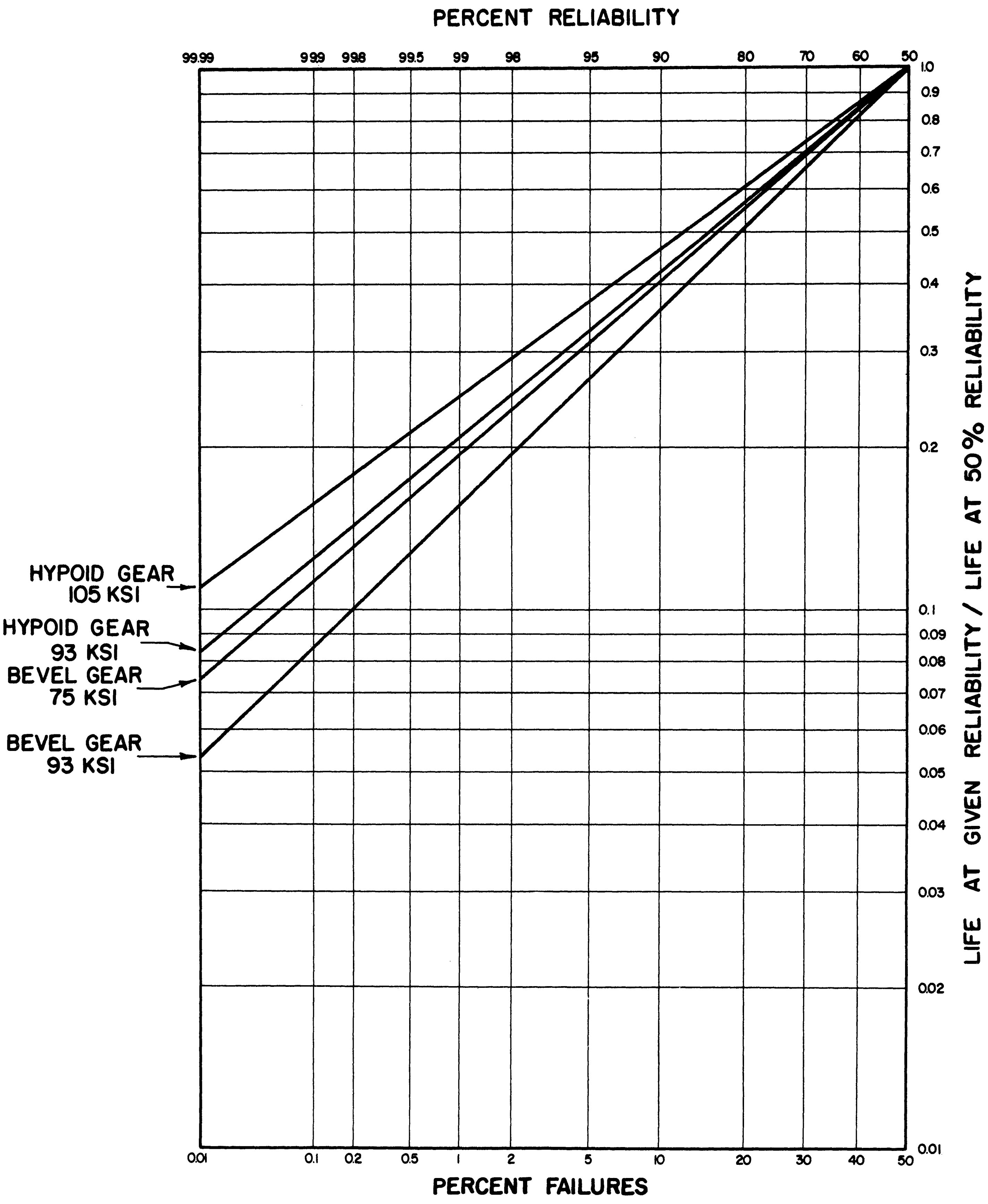

Figure 8. Design Life Factors at Different Reliabilities - Bevel and Hypoid Gears.

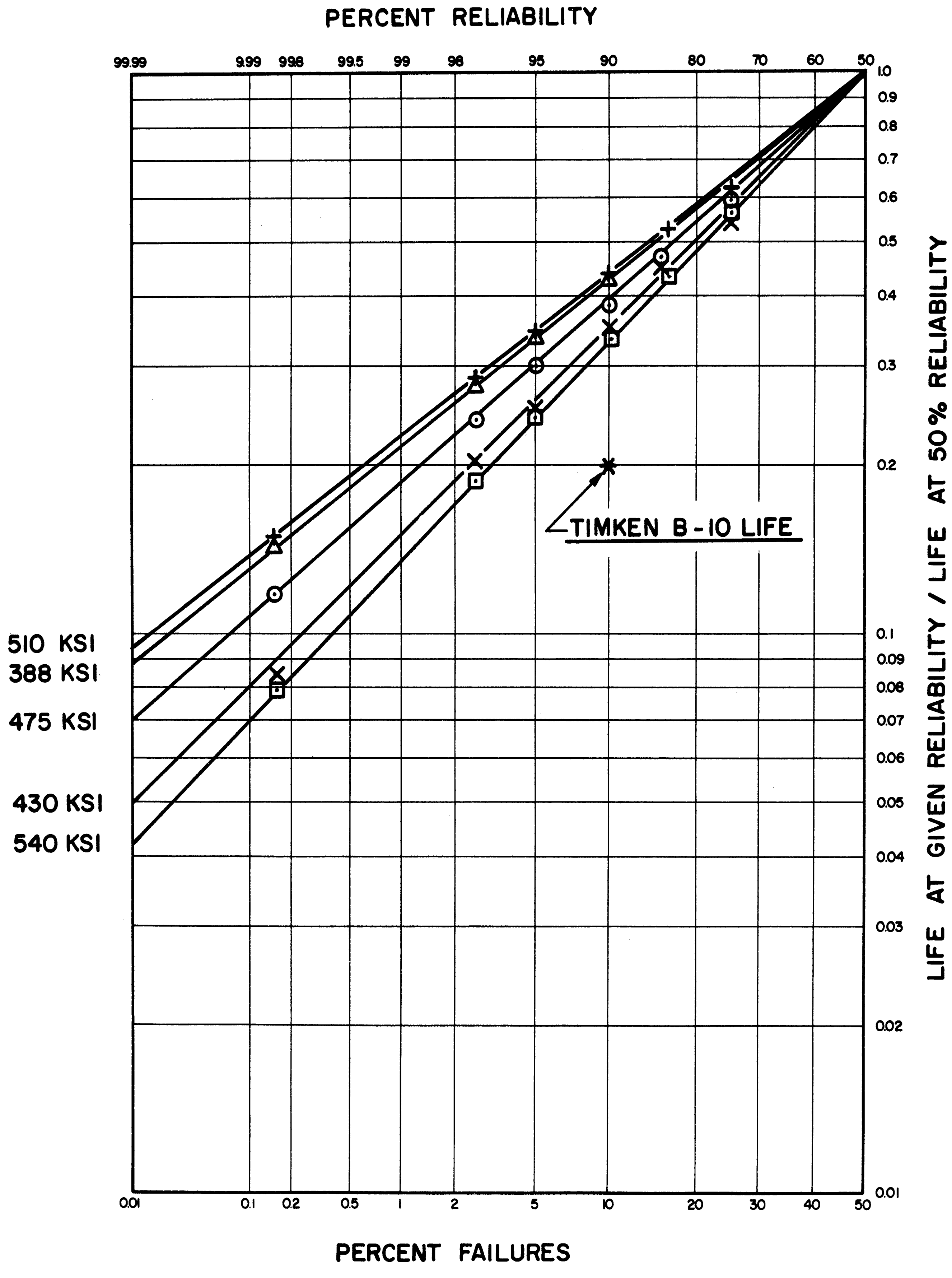

Figure 9. Design Life Factors at Different Reliabilities - Radial Ball Bearings.

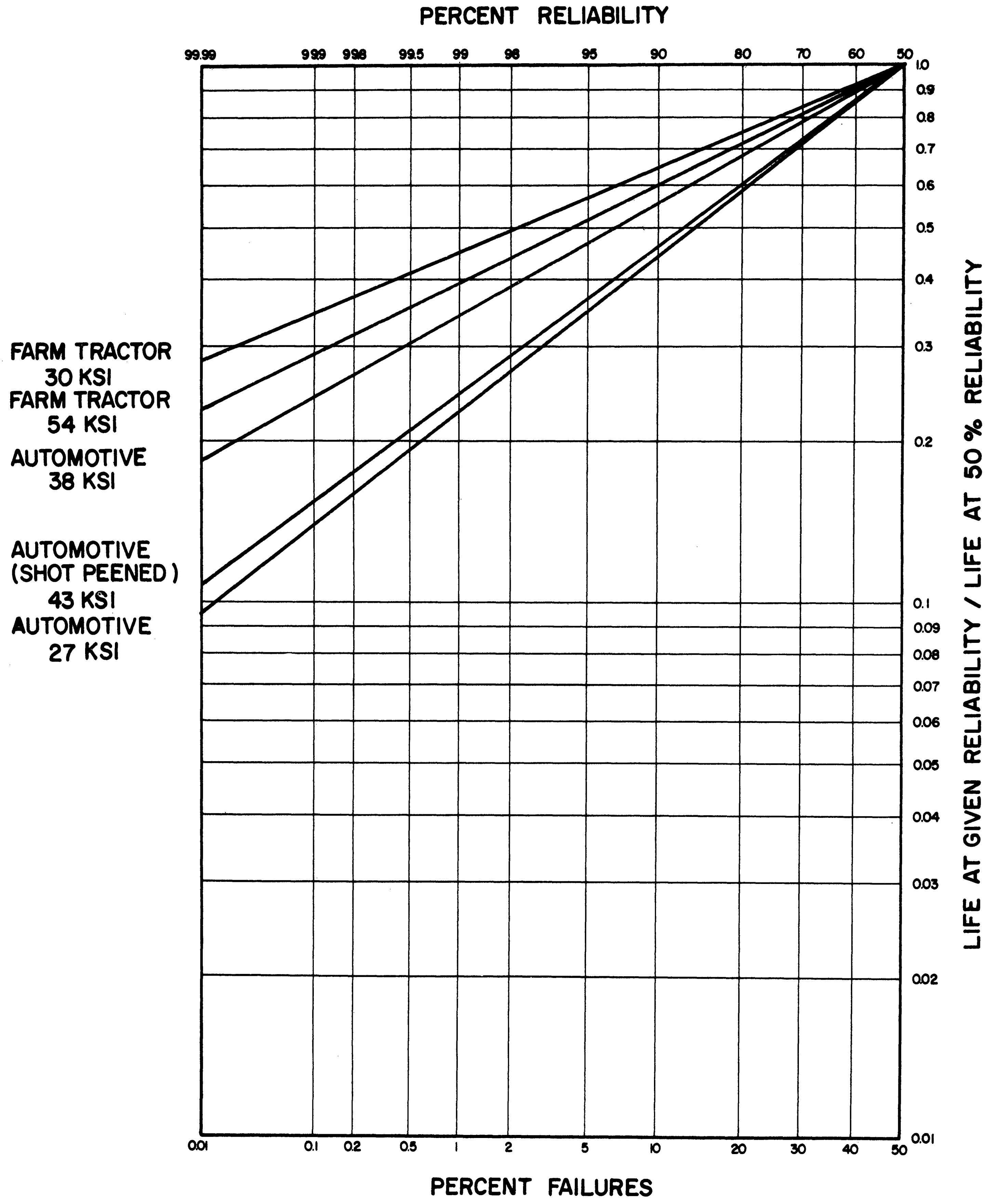

Figure 10. Design Life Factors at Different Reliabilities - Rear Axle Shafts.

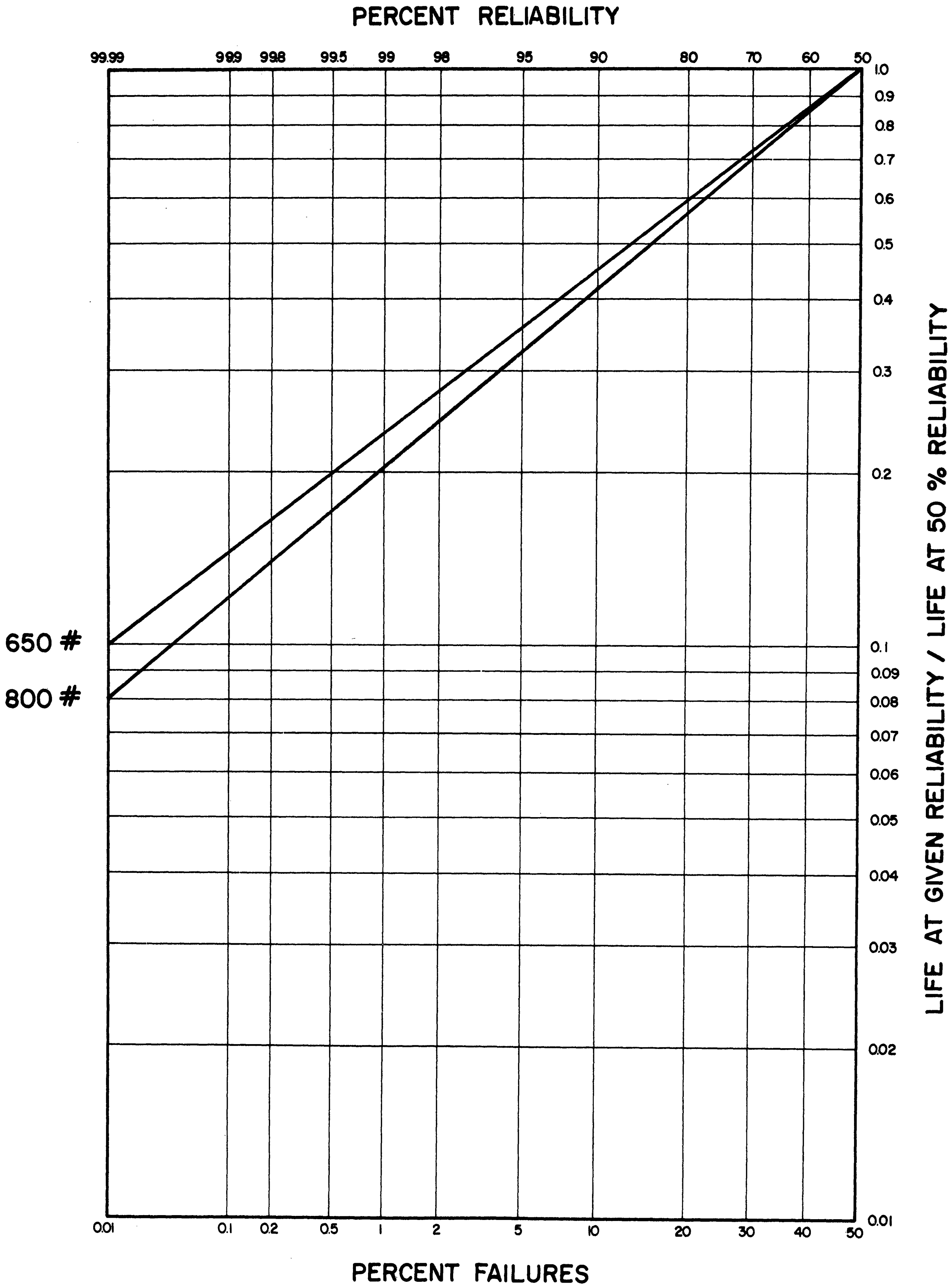

Figure 11. Design Life Factors at Different Reliabilities - Roller Chains.

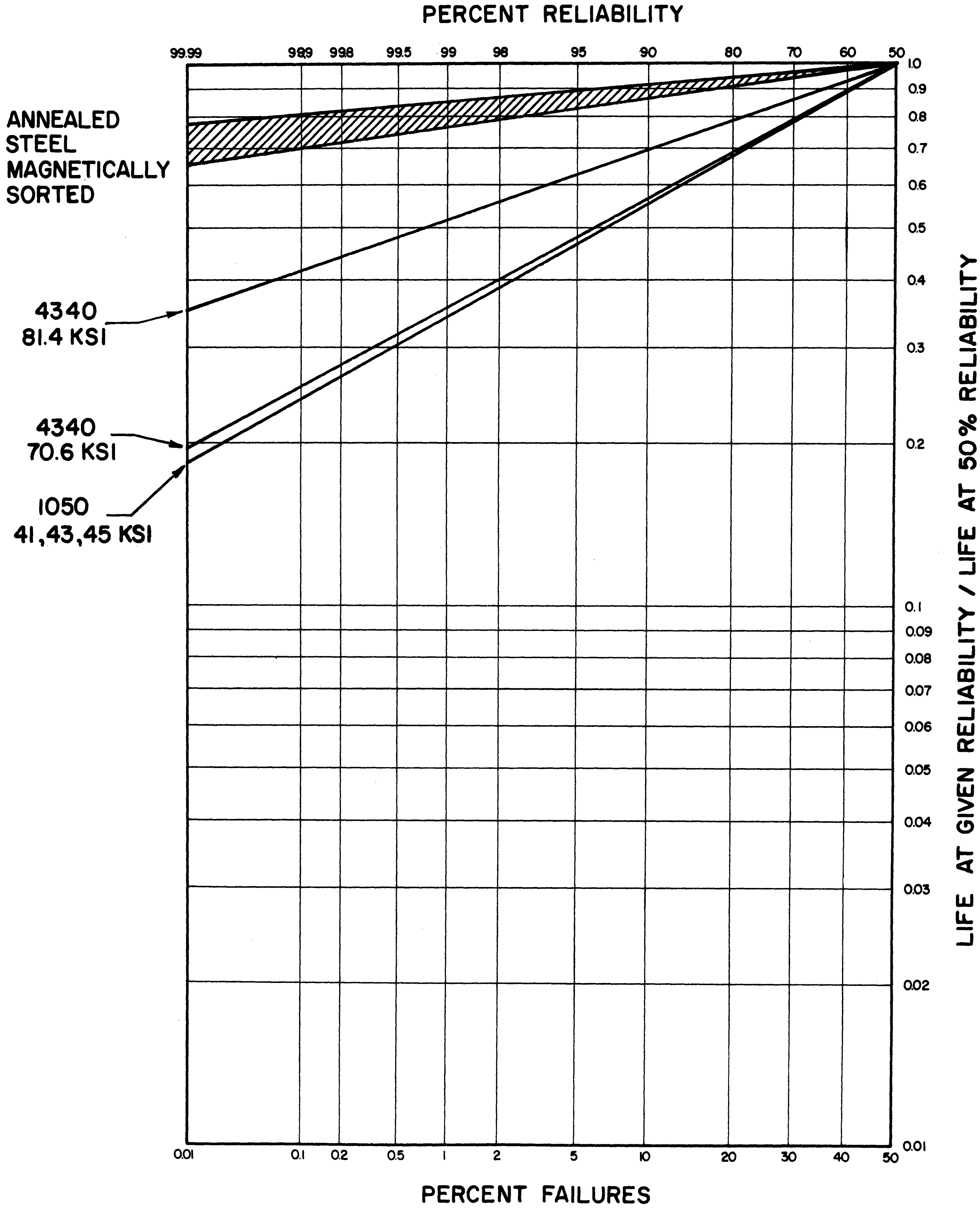

Figure 12. Design Life Factors at Different Reliabilities - Some Steels.

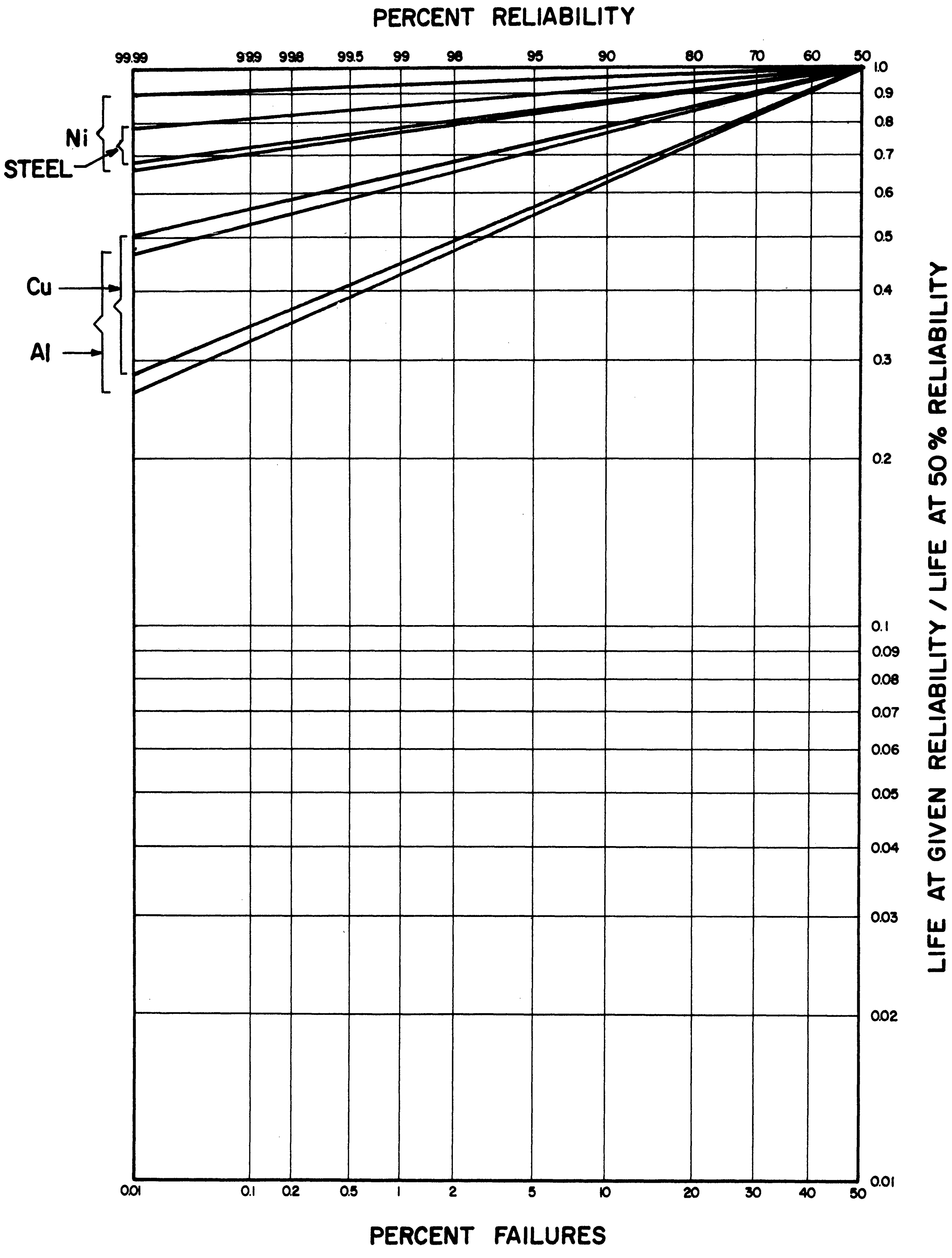

Figure 13. Design Life Factors at Different Reliabilities - Annealed Steel and Nickel Magnetically Presorted.

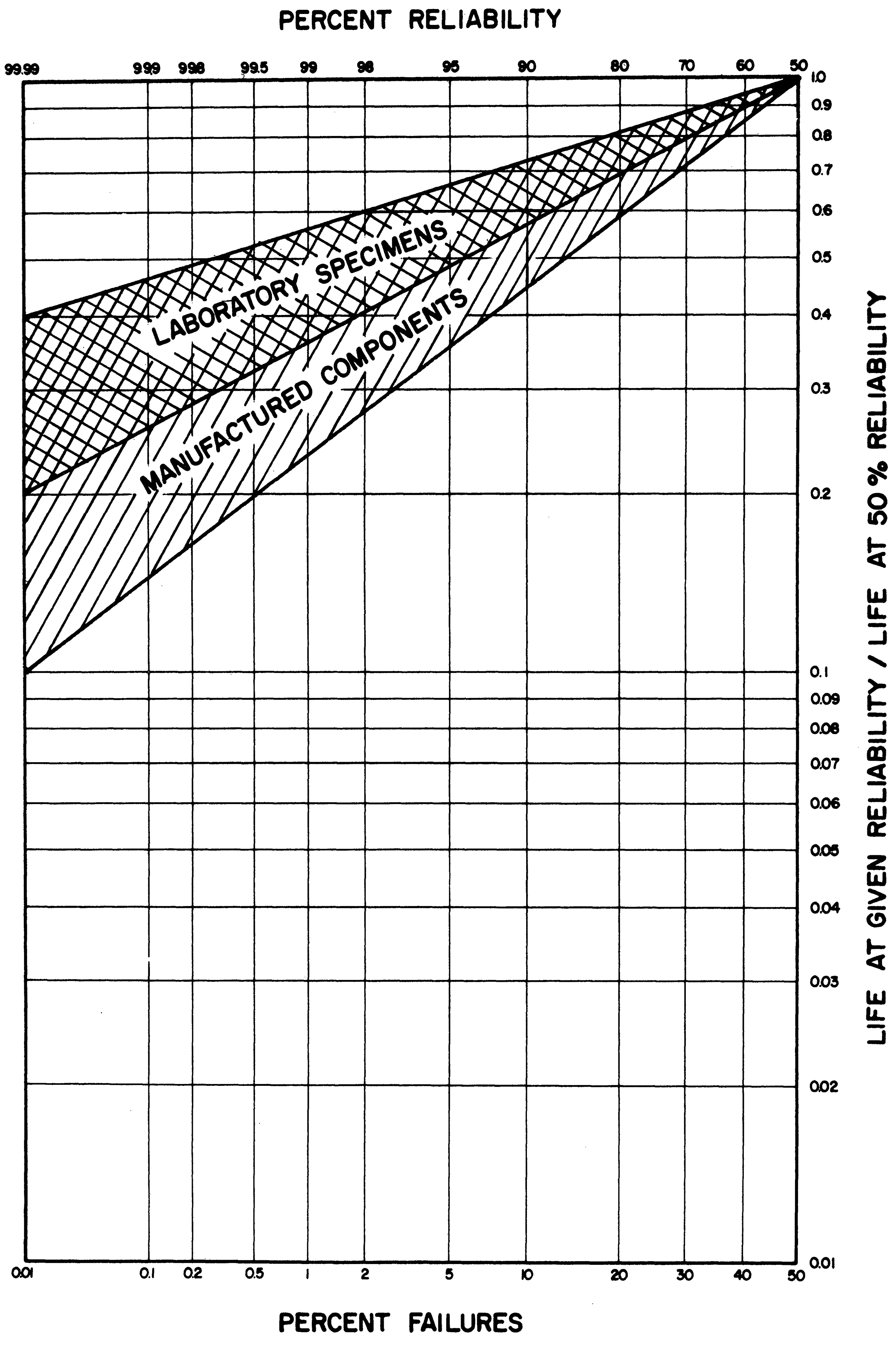

Figure 14. Design Life Factors at Different Reliabilities - Comparison Between Laboratory Specimens and Manufactured Components.

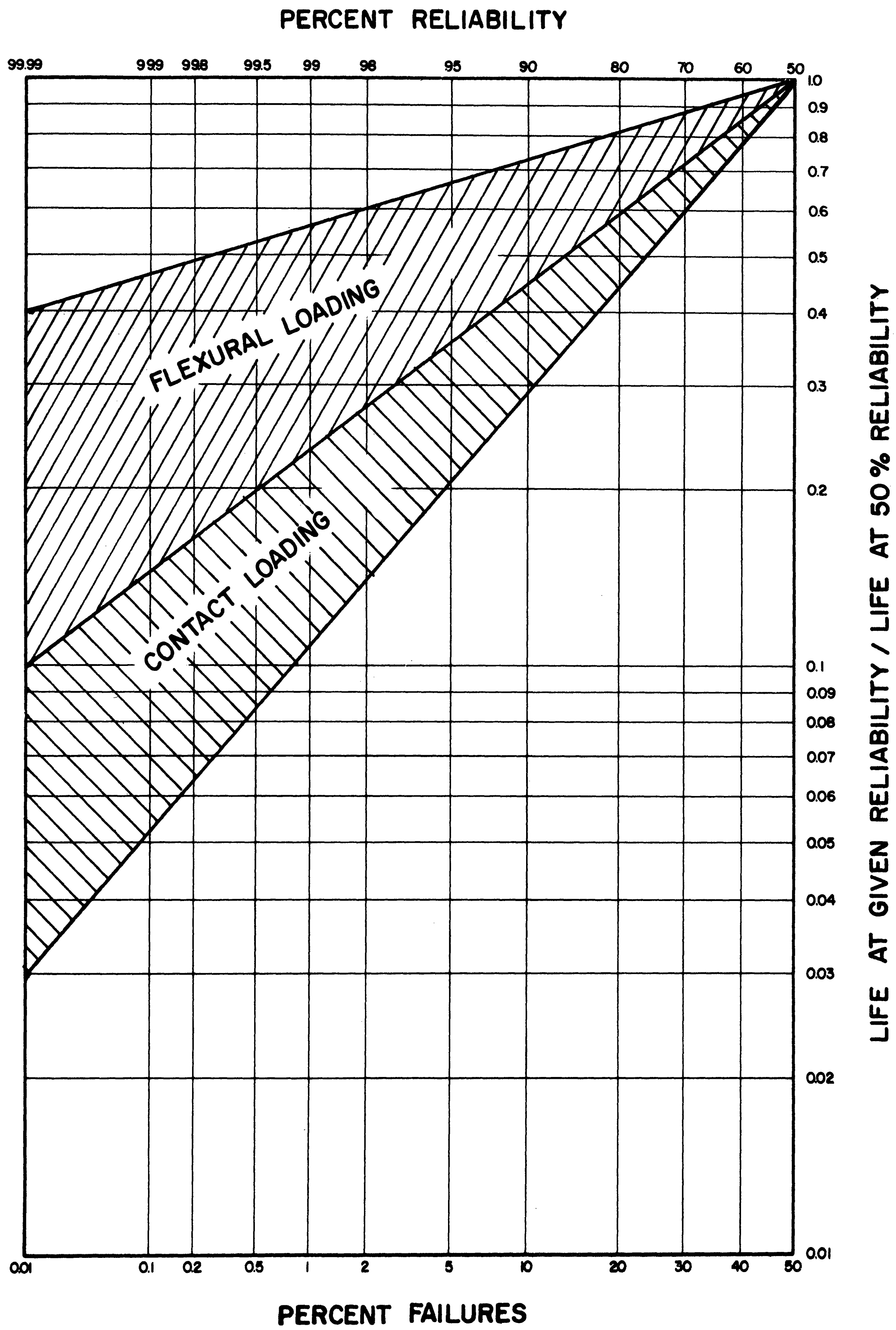

Figure 15. Design Life Factors at Different Reliabilities - Comparison Between Parts Subjected to Flexural Loading and Contact Loading.

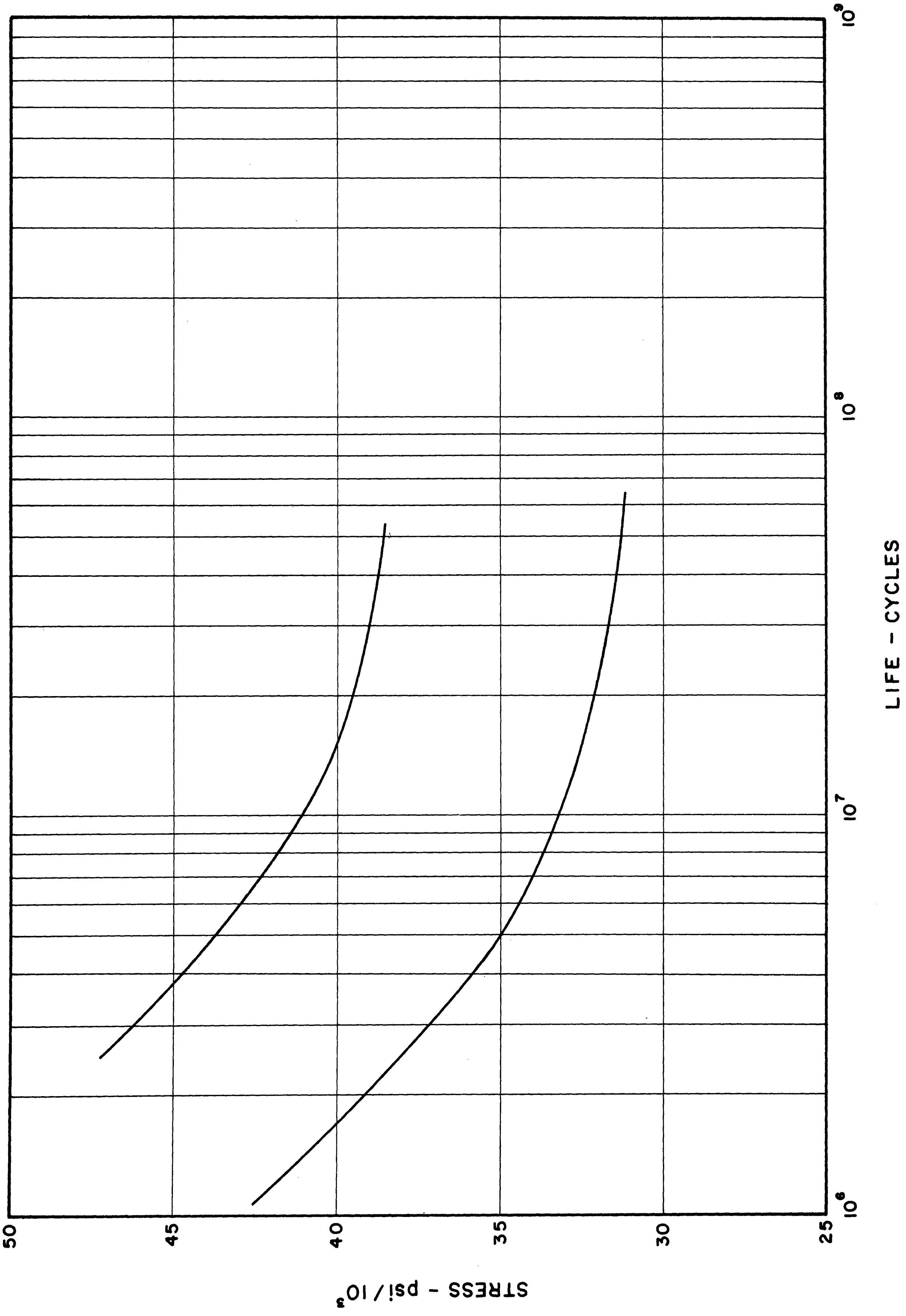

Figure 16. Scatter Band of Monel Metal[8].

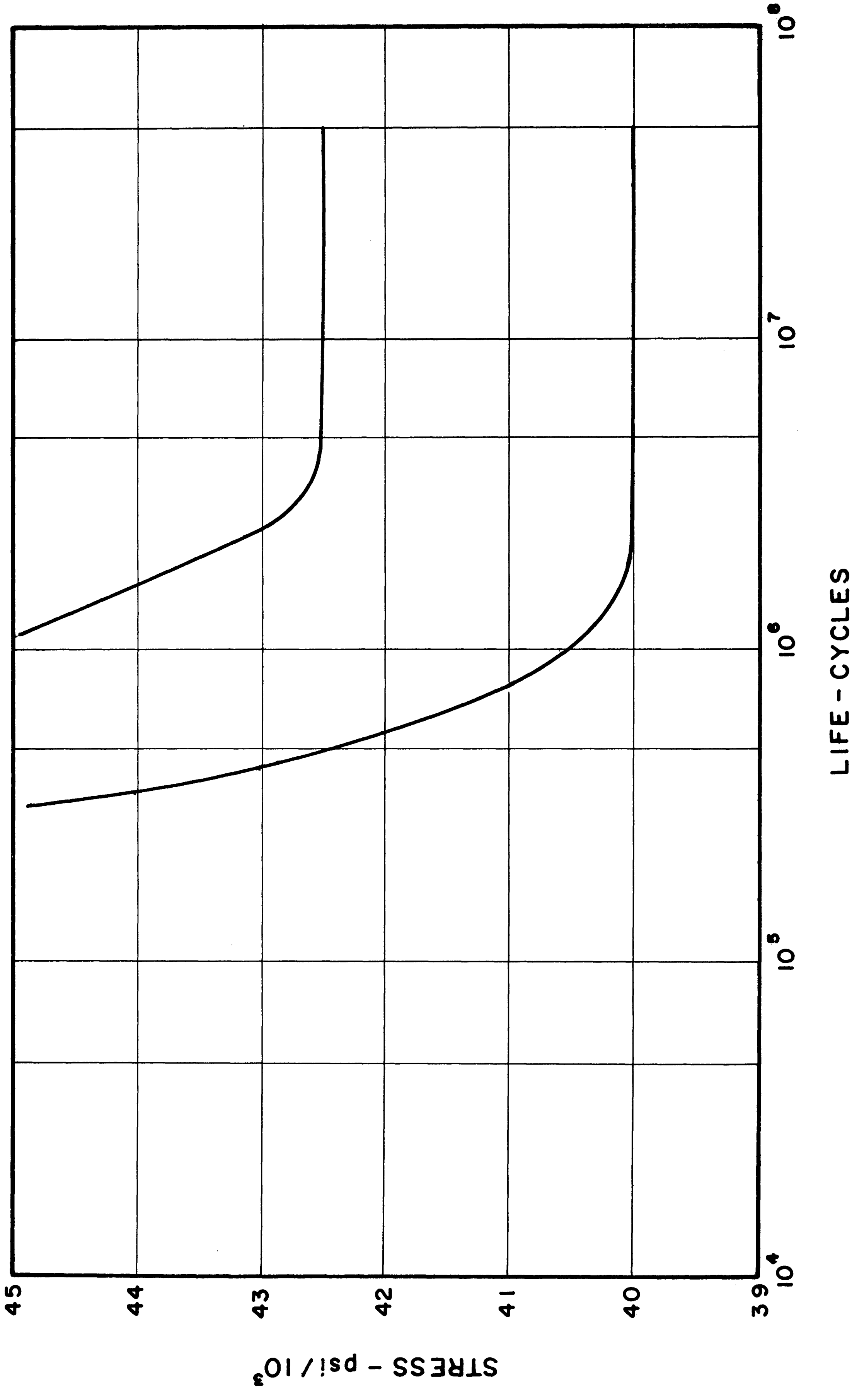

Figure 17. Scatter Band of 1050 Steel[9].

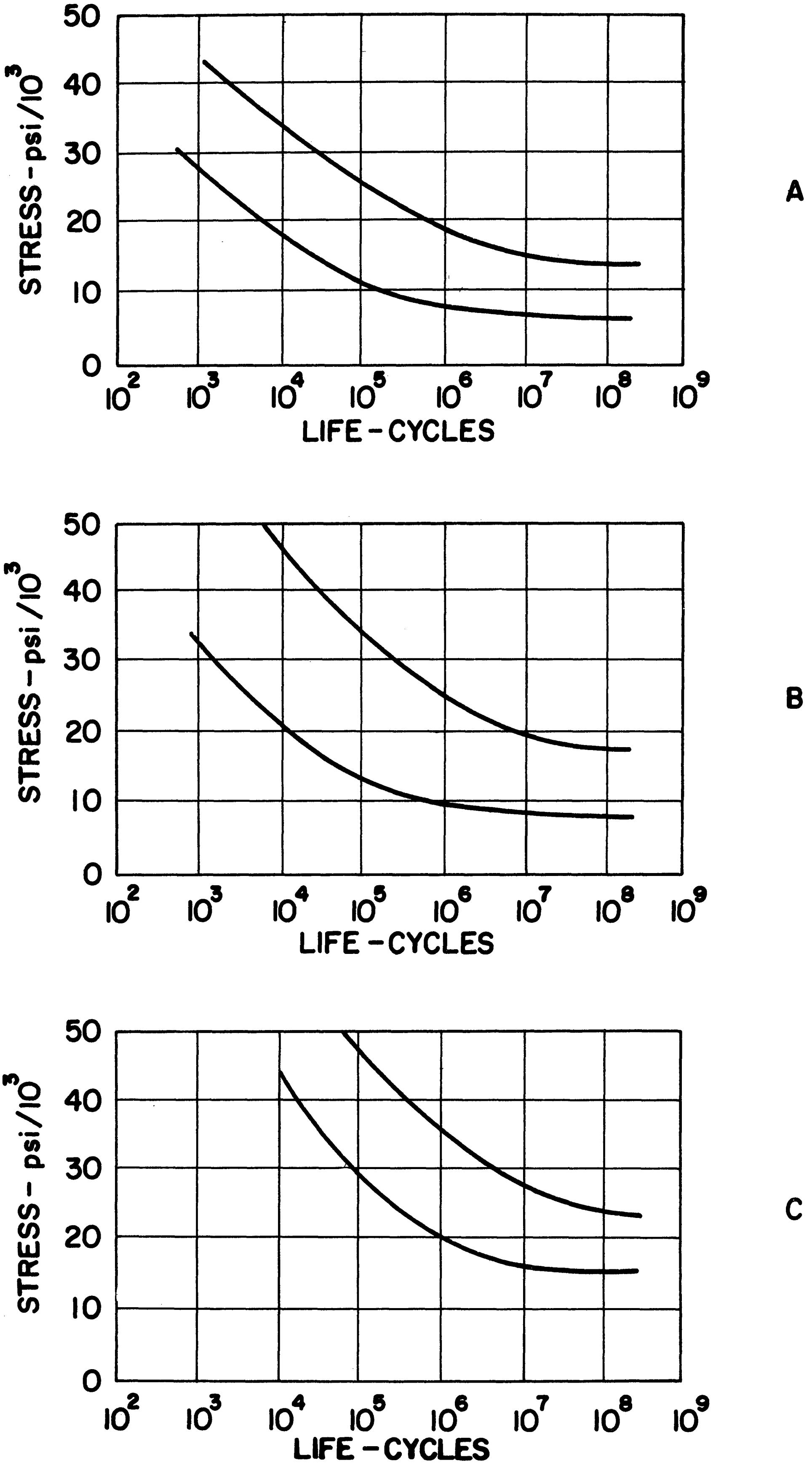

Figure 18. Scatter Band of Aluminum Alloys - A: Sand Cast; B: Permanent Mold; C: Wrought[10].

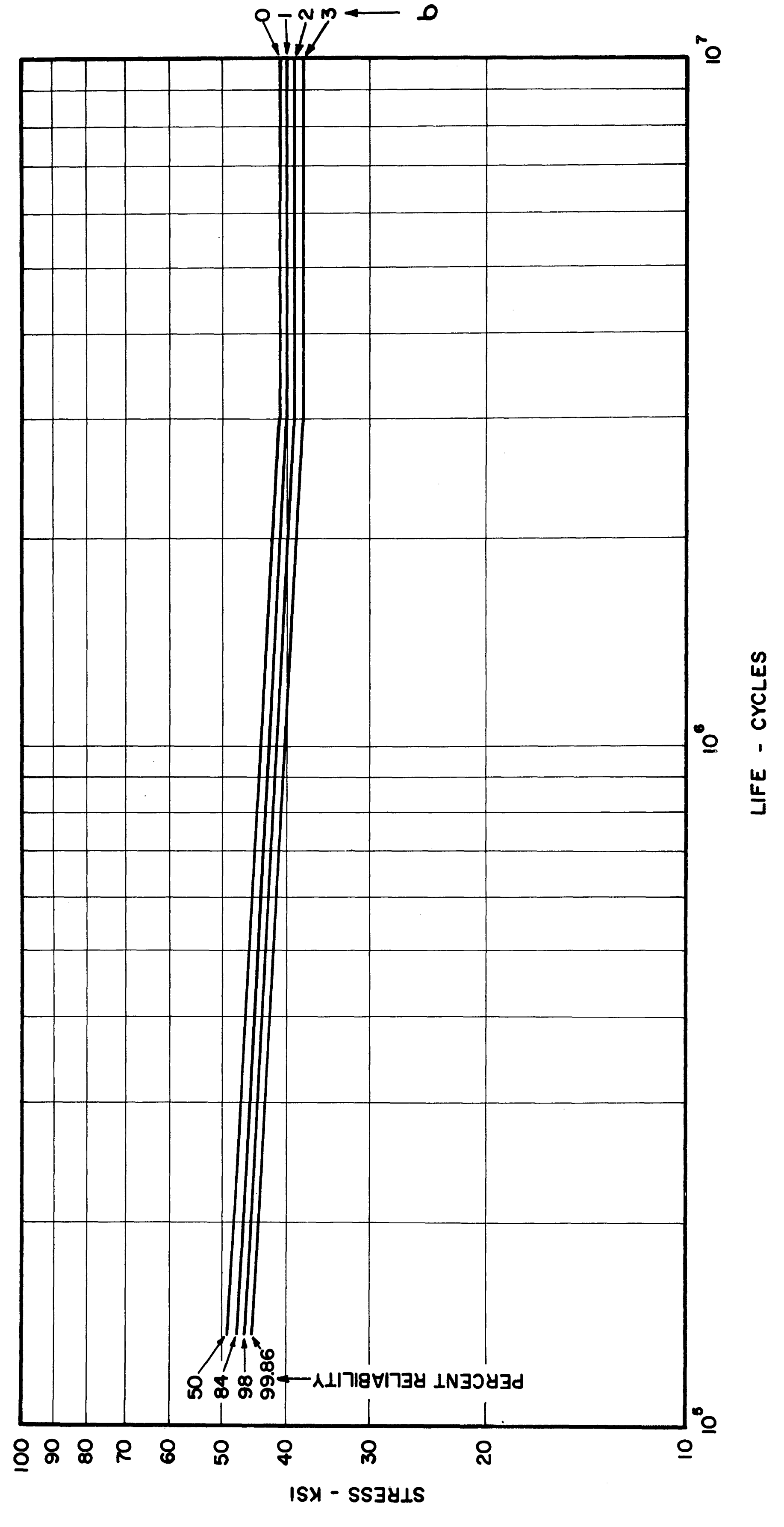

Figure 19. Stress-Life Relationship at Various Reliabilities - 1050 Steel, $81R_b$.

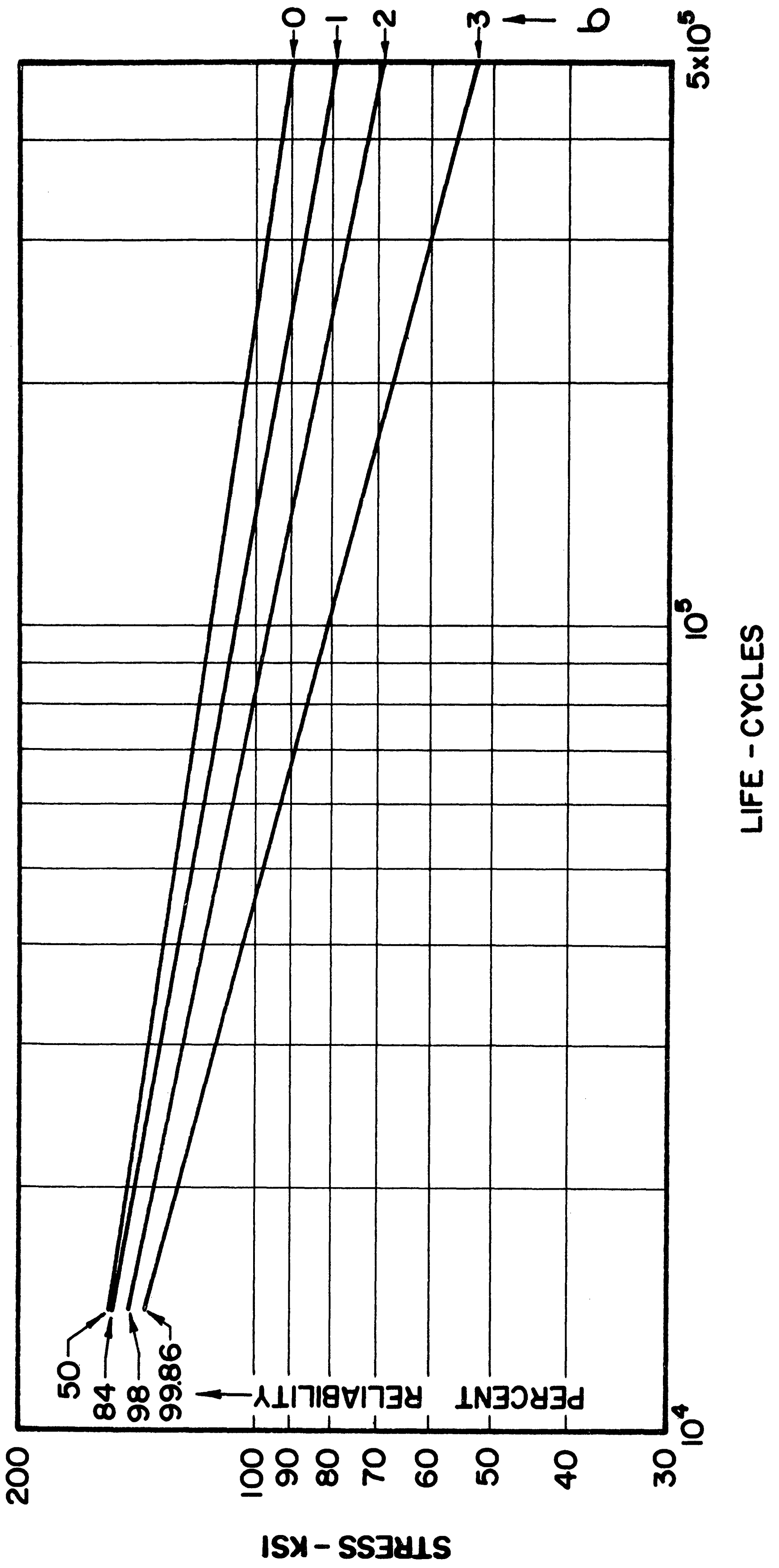

Figure 20. Stress-Life Relationship at Various Reliabilities - 4340 Steel, 363 BHN.

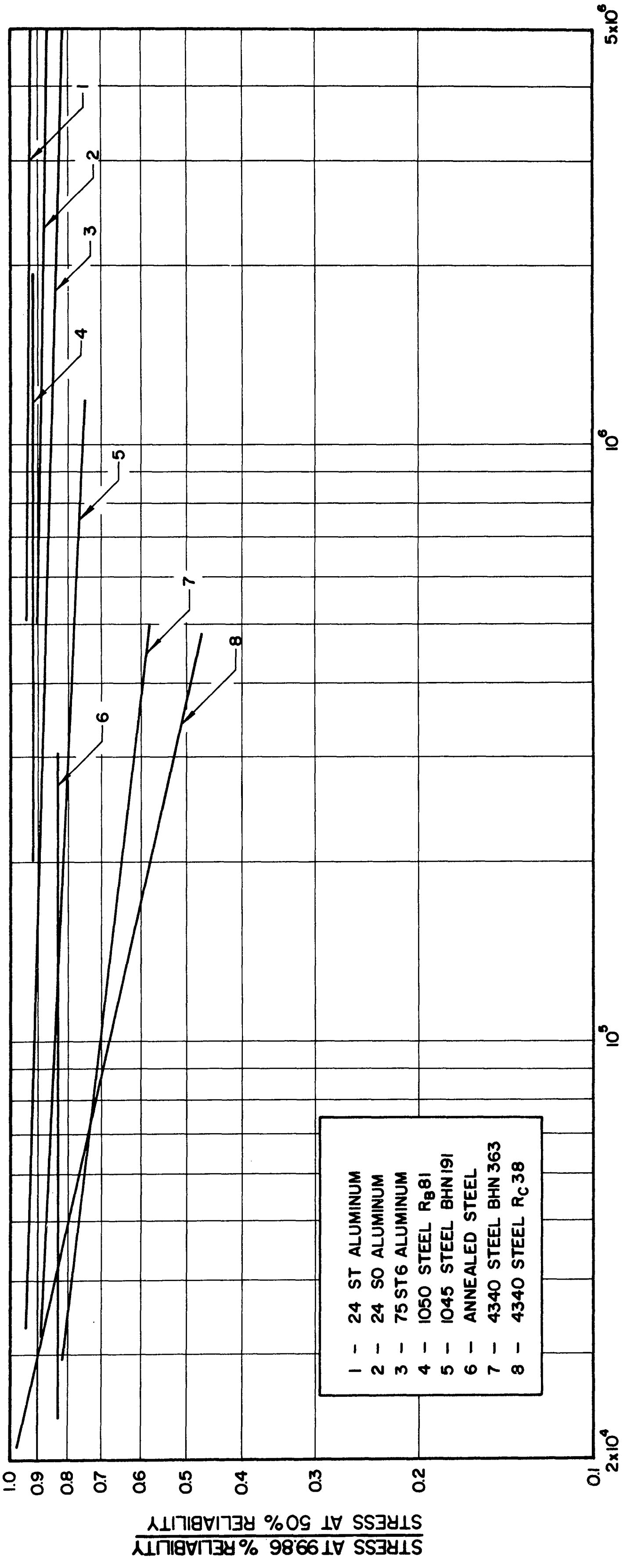

Figure 21. Stress-Life Relationship at Various Lives - Some Materials.

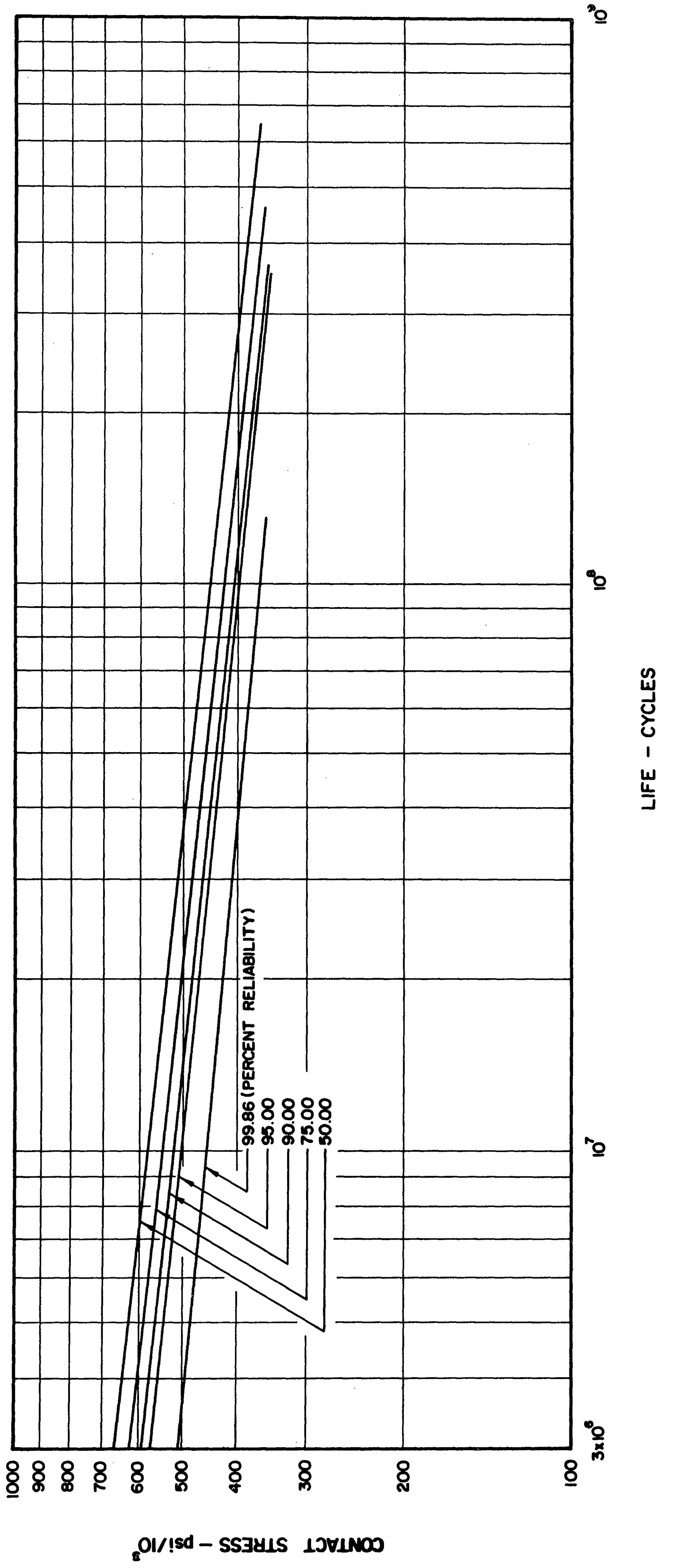

Figure 22. **Stress-Life** Relationship at Various Reliabilities - Radial **Ball Bearings.**

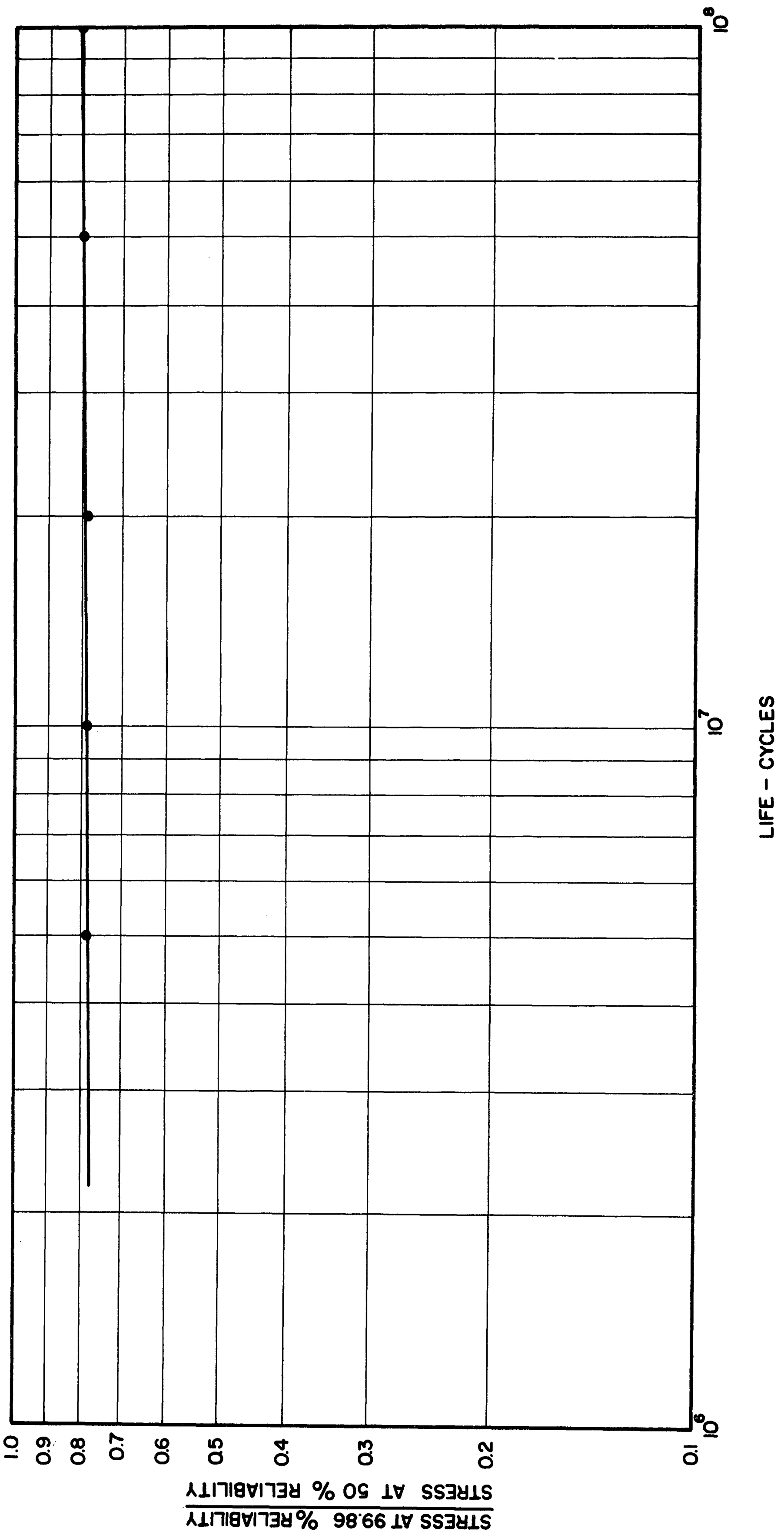

Figure 23. Design Stress Factors at Various Lives - Radial Ball Bearings.