Southwestern Petroleum Short Course Proceedings, April 23-24, 2008, Lubbock, Tx, p. 23-28.

<u>Predicting Sucker Rod Life</u>

Paul M. Bommer, Ph.D., Senior Lecturer, Department of Petroleum and Geosystems Engineering, The University of Texas at Austin

<u>Motivation:</u> This paper presents a method for predicting the life of sucker rods. It is based on the maximum and minimum stress on a rod during a stroke. The result is a Constant Life Diagram for the rod (sometimes referred to as a Haigh Diagram). The step-wise procedure used to construct the diagram is described. A comparison is made with the other possibilities for predicting the life of the rod. The Constant Life Diagram can be constructed from laboratory data, but a more practical diagram can be constructed using field data.

<u>Material Fatigue:</u> A sucker rod is subjected to fluctuating loads during one stroke. The fluctuations are repeated on every stroke and are characterized by the maximum and the minimum load that occur during the stroke. A sucker rod can tolerate only a given number of cycles (strokes) under the fluctuating loads before the rod fails. The rod stress is the rod load divided by the cross-sectional area of the rod. The rod fails at an apparent maximum stress that is normally well below the minimum tensile strength of the rod and often well below the minimum yield stress of the rod. This type of failure is called fatigue.

The petroleum industry is unique in that we allow sucker rods to run to the point of failure before making repairs. In other professions, such as aeronautical and structural engineering, the prediction of fatigue failure is of extreme importance. For example, several high-profile disasters were the result of metal fatigue. In the early 1950's two British Comet jetliners came apart in flight because of fuselage breaches that started as fatigue cracks at the corners of square shaped windows. Notice that you do not see square shaped airliner windows today. In 1988 the upper fuselage of an Aloha Airlines 737 parted during take-off due to metal fatigue in the skin. In 1985 the tail section of a Japan Airlines 747 dropped off after an internal bulk head suffered metal fatigue in a riveted section. Lastly, the Mississippi River Bridge at Minneapolis suffered metal fatigue in load bearing supports in 2007, causing it to fall into the river.

For sucker rods, fatigue is a crack that starts at a minor imperfection or a point of damage such as a hammer blow, a nick or a corrosion pit. As the rod is moved through the load cycle the small crack begins to grow through the cross-sectional area of the rod. At first the rod has sufficient strength to tolerate the loss of cross-sectional area as the crack spreads. Finally, the crack is large enough so that the remaining cross-sectional area is insufficient to support the load and the rod parts suddenly and cataclysmically. At the time of failure the apparent maximum stress on the rod is the maximum load divided by the total cross-sectional area of the rod. The apparent maximum stress will be below the tensile strength of the rod. However, the actual stress being carried by the rod is the load divided by the area remaining intact. The actual stress will be equal to the tensile strength of the rod at the time the rod fails.

Sucker Rod Design and Fatigue Life: The sucker rod design approach used today does not explicitly predict the fatigue life of the rod. The current design method requires that the loads are within a predetermined area that will give a service life deemed acceptable. Not withstanding, the longer the life, the fewer the repairs and non-productive down time. Further, the ability to predict the life of sucker rods would allow the design engineer to look into the future for budgets and the over all economics of a well or a field.

S-N Diagrams: Early work in fatigue created the stress-life (sometimes called a Wöhler or S-N) diagram. A stress-life diagram plots the stress amplitude of a cycle versus the number of cycles to failure for a given laboratory specimen. A stress-life diagram taken from the early work of Dale and Johnson[1] is shown in Fig. 1. The stress amplitude is defined using equation (1).

$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2} \text{ ...... (1)}$$

Several properties can be determined from Fig. 1. The intercept of the stress line with a life of 1/4 cycle is the tensile strength of the material. The stress where the lab specimen data become flat is the endurance limit of the specimen. Theoretically, at or below the stress represented by the endurance limit, the material has an infinite life. This phenomenon is only observed in the laboratory. Unfortunately, real world environments are harsh, with corrosion, abrasion, and damage affecting the life of the rod. The dashed "Real World" line shows that even at small stress amplitudes the specimen will fail at some point. By definition, the endurance limit for "Real World" environments is the stress amplitude under which the rod will have a life of 10 million $\left(1x10^7\right)$ cycles[2]. The use of this endurance limit definition does not imply infinite life at this stress amplitude, but a finite life of 10 million cycles.

Constructed correctly, a stress-life diagram is for a fully reversed lab test specimen. This means that the maximum stress is in tension and the minimum stress is an identical value in compression. The stress amplitude for such a test is the value of the maximum stress. For such a test the mean stress as defined by equation (2) is zero.

$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \text{ ...... (2)}$$

It is tempting to use a stress-life diagram for fluctuations that have different mean stresses. Unfortunately, the shape of the stress-life diagram changes for different mean stresses. Therefore, the stress-life diagram will not be representative for more than one set of maximum and minimum stress and the resulting mean stress. This is the main reason the S-N diagram is not used for sucker rod design.

To avoid this problem, the API adopted a Modified Goodman Diagram to define the stress fluctuations during a stroke.

API Modified Goodman Diagram: Goodman's work [3] considered steel specimens that were cycled through a variety of minimum and maximum loads. He considered 4 million cycles before failure as an "infinite life" and he constructed a diagram that showed the acceptable stress fluctuations that produced this life.

The Modified Goodman Diagram (MGD) we currently use for API sucker rod analysis [4] is shown in Fig. 2. This diagram shows stress as a fraction of the minimum tensile strength of a rod. The intercept of the maximum stress line at zero minimum stress is defined as the fatigue strength of the rod and is related to the required number of cycles [5]. Goodman's experimental correlation has a fatigue strength equal to one half the minimum tensile strength and a life of 4 million cycles. The API modification of Goodman's diagram uses fatigue strength of one quarter of the minimum tensile strength and a life of 10 million cycles. Recall the definition of endurance limit specifies a life of 10 million cycles. So, the API fatigue strength is sometimes called the endurance strength and is equal to one quarter of the minimum tensile strength of the rod. The API MGD is not specific to any particular rod metallurgy, but is designed for average carbon steel.

A rod will tolerate more than 10 million cycles if the fatigue strength is less than one quarter of the minimum tensile strength of the rod. The expected life $\left(N_f\right)$ is an exponential function of fatigue strength $\left(S_f\right)$ as shown by equation (3) where the constants "a" and "b" are properties of the rod [5].

$$S_f = aN_f^b \text{ ...... (3)}$$

It is important to note that the API Modified Goodman Diagram is not specific to any particular rod metallurgy and is designed around a rod life of 10 million cycles. In order to calculate the life of a rod using equation (3) the rod constants "a" and "b" must be determined experimentally or estimated by calculation. Therefore, it is not possible to use the unaltered API MGD to determine the life expectancy of a rod other than 10 million cycles.

The Constant Life Diagram: The constant life diagram, also called a Haigh diagram after the founder, avoids the limitations of the S-N and API Modified Goodman Diagrams. The constant life diagram can be constructed from field data for any rod type, specific to any producing environment, using any variety of stress fluctuations (thus any mean stress), and will show the resulting life expectancy of the rod for any stress fluctuation.

A constant life diagram for an example data set from a South Texas well is shown in Fig. 3. The constant life diagram of Fig. 3 uses the maximum and minimum stress for a cycle divided by the minimum tensile strength of the rod. The example data set is shown in Table 1.

Using Fig. 3 for an example rod design, if the minimum stress divided by the minimum tensile strength equals 0.1 and the maximum stress divided by the minimum tensile strength equals 0.25, the predicted rod life is 20 million strokes. Assuming a design speed of eight strokes per minute, the predicted rod life is 4.75 years before failure.

Construct a Constant Life Diagram: A data set from one South Texas well using API Class D rods is shown in Table 1. The maximum and minimum stresses were calculated using a solution to the well known one dimensional wave equation any time the pumping operation was changed or a rod failed. The calculations were made using the commercial program Rod Star created by Theta Software.

The average stresses over the life of the rod were computed using equation (5).

$$\bar{\sigma} = \frac{\sum_{i=1}^{j} n_i \sigma_i}{\sum_{i=1}^{j} n_i} \quad ...... (6)$$

The stresses are computed because it is not currently possible to directly measure the loads at depths other than the surface in the rod string. This computation step is important and is one reason why a constant life diagram has not been previously used for sucker rods. The stress fluctuation over the entire life of the rod must be computed for this diagram to have any meaning. To do this with reasonable accuracy requires that the pumping conditions over time be accurately recorded in the data set. For example, the pumping depth, plunger size, and rod string are normally well documented in the well record. Stroke length and pumping speed changes often are not. The example data set, shown in Table 1, references only the rod parts. For the sake of brevity the numerous rod string, pump size, stroke, and speed changes have been left out of Table 1. For every operational change the new stress fluctuation was calculated and used to compute the stress averages when a particular rod failed.

The data points of the average maximum and minimum stresses divided by the minimum tensile strength of the rods for every rod failure were plotted on the diagram and the constant life lines drawn to fit the number of cycles to failure for the data. There is obvious data scatter in the example data set. The choice of the shapes of the constant life lines is certainly open to statistical interpretation. The constant life lines shown in Fig. 3 are constructed to predict life conservatively. However, the endpoint of all the constant life lines must be 1.0 where the load becomes static at the minimum tensile strength. Although not shown on the scale used in Fig. 3 the constant life lines all converge at the tensile end point of 1.0. Fig. 3 does not extend into the area of compressive loading. Compression is to be avoided with sucker rods because the rods tend to buckle when placed in compression.

Laboratory tests of rods can obviously be used to create a constant life diagram. However, the use of real world data retains the environmental effects and the effects of the actual pumping operation.

Conclusions: The use of field data allows the creation of "Real World" constant life diagrams for the prediction of sucker rod life. The use of field data is important because both the environmental and operational effects on rod life are retained. The constant life diagram can be created for one well or one field and for any given rod type. The constant life approach avoids the limitations the S-N and API Modified Goodman Diagrams.

The creation of constant life diagrams allows the design engineer to predict the service life of the rods. Additionally, such a diagram could be used along with a load cell and a variable speed motor to control the speed of the pumping unit in order to reach a pre-determined life. This application could be in the form of a computer controlled unit or it can be done manually. The variable speed motor is necessary for a computer controlled unit. If done manually, the speed can be adjusted by changing sheaves and/or installing a jack shaft [6].

If the reader has a data set and wishes a constant life diagram for the rods, please submit the data set to the author at pmbommer@mail.utexas.edu. A constant life diagram will be created and returned if the data set is of sufficient quality.

References:

(1) Dale, D.R. and Johnson, D.O., "Laboratory and Field Endurance Values of Sucker-Rod Materials", API Drilling and Production Practice, 1940, pp. 209-218.
(2) Suresh, S., "Fatigue of Materials", 2nd Edition, Cambridge Univ. Press, 1998, pp. 223.
(3) Goodman, John, "Mechanics Applied to Engineering", Longmans, Green and Co., London, 1914, pp. 631-636.
(4) API Recommended Practice 11BR, 8th ed., API, Dallas, October 1989.
(5) Shigley, J.E., Mischke, C.R., and Budynas, R.G., "Mechanical Engineering Design", 7th ed., McGraw-Hill, New York, 2004, Chapter 7.
(6) Bommer, P.M. and Shrauner, D., "The Benefits of Slow Speed Pumping", Southwestern Petroleum Short Course Proceedings, April 25-26, 2007, Lubbock, Tx, p.1-10.

This paper is reprinted from the Proceedings of the Fifty-Fifth Annual Meeting of the Southwestern Petroleum Short Course, April 23-24, 2008, Lubbock, TX, pages 23-28.

Nomenclature and Units:

$\sigma_{\max}, S_{\max}$	Maximum stress on a sucker rod (psi)
$\sigma_{\min}, S_{\min}$	Minimum stress on a sucker rod (psi)
$\sigma_a,\ S_{amp}$	Stress amplitude (psi)
σ_m, S_{mean}	Mean stress (psi)
$\bar{\sigma}$	Average stress over a given number of strokes (psi)
a , b	rod properties that relate the number of cycles to fatigue strength a has units of psi and b is dimensionless
n_i	number of cycles at a given stress level (σ_i)
N_f	number of cycles associated with a given fatigue strength
S_f	fatigue strength (psi) associated with a set number of cycles
$T_{\min}$	Minimum tensile strength of a sucker rod (psi)

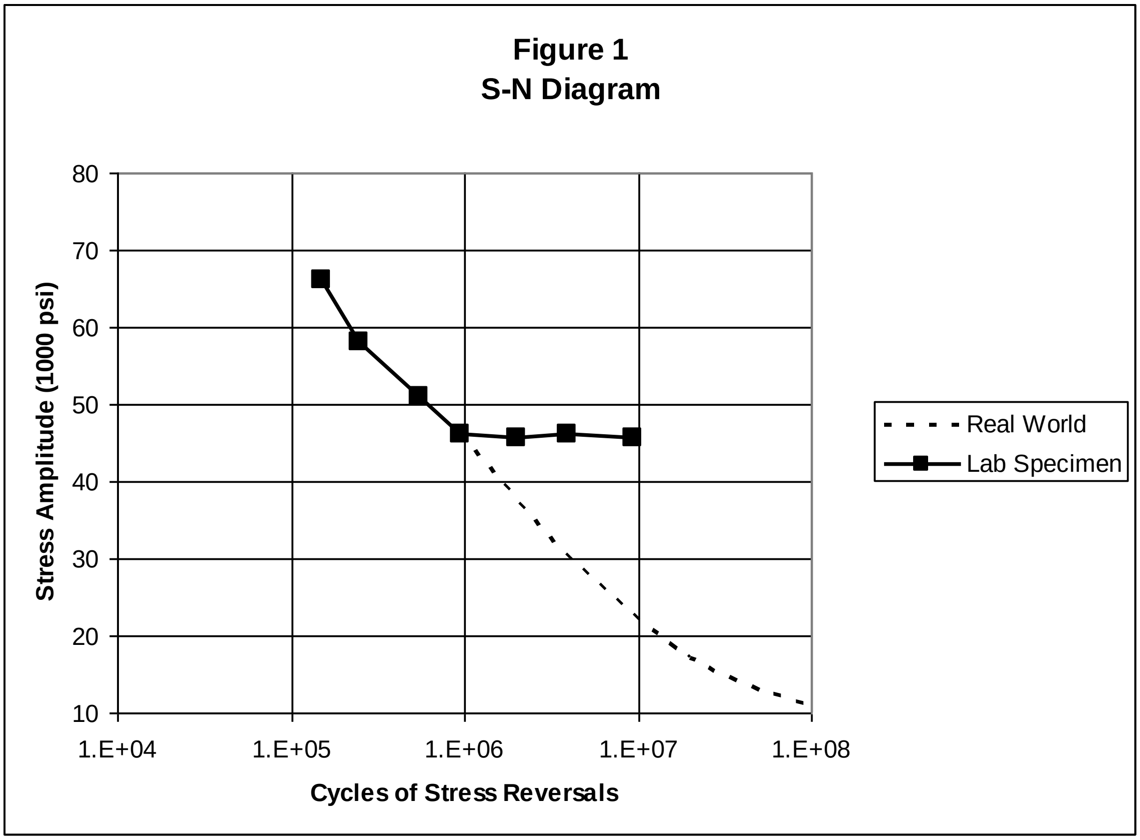


Figure 1
S-N Diagram
80
70
60
50
40
30
20
10
Stress Amplitude (1000 psi)
1.E+04
1.E+05
1.E+06
1.E+07
1.E+08
Cycles of Stress Reversals
Real World
Lab Specimen

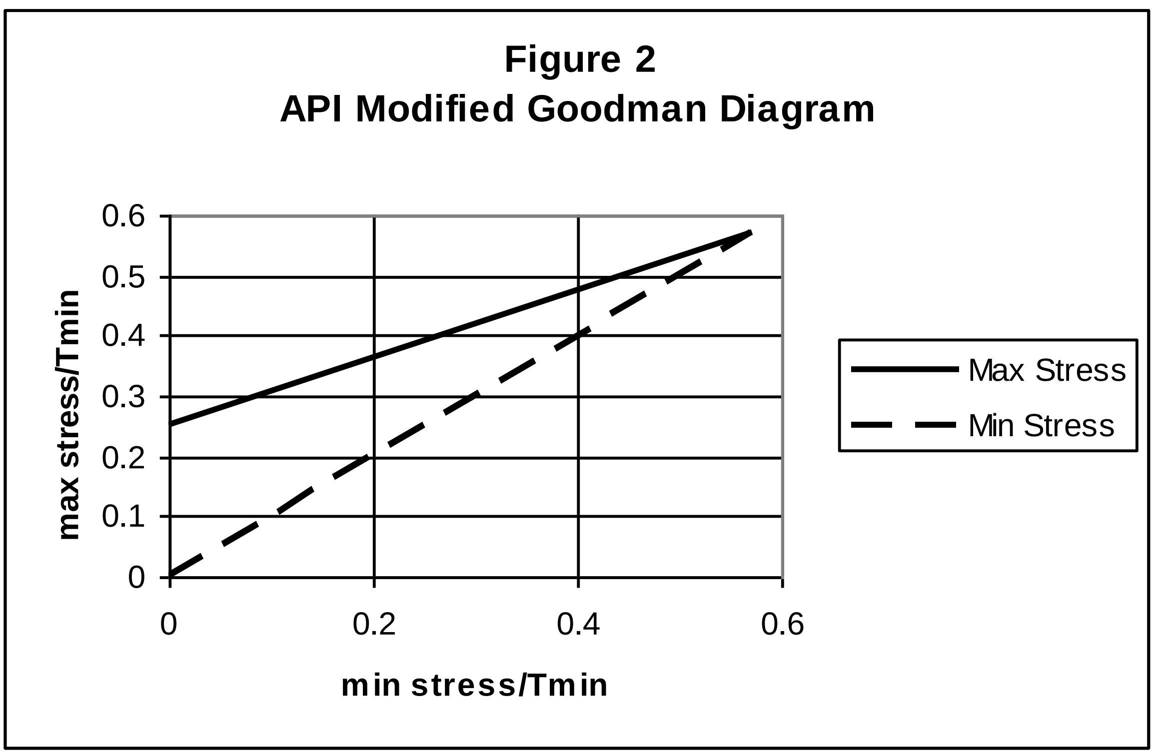
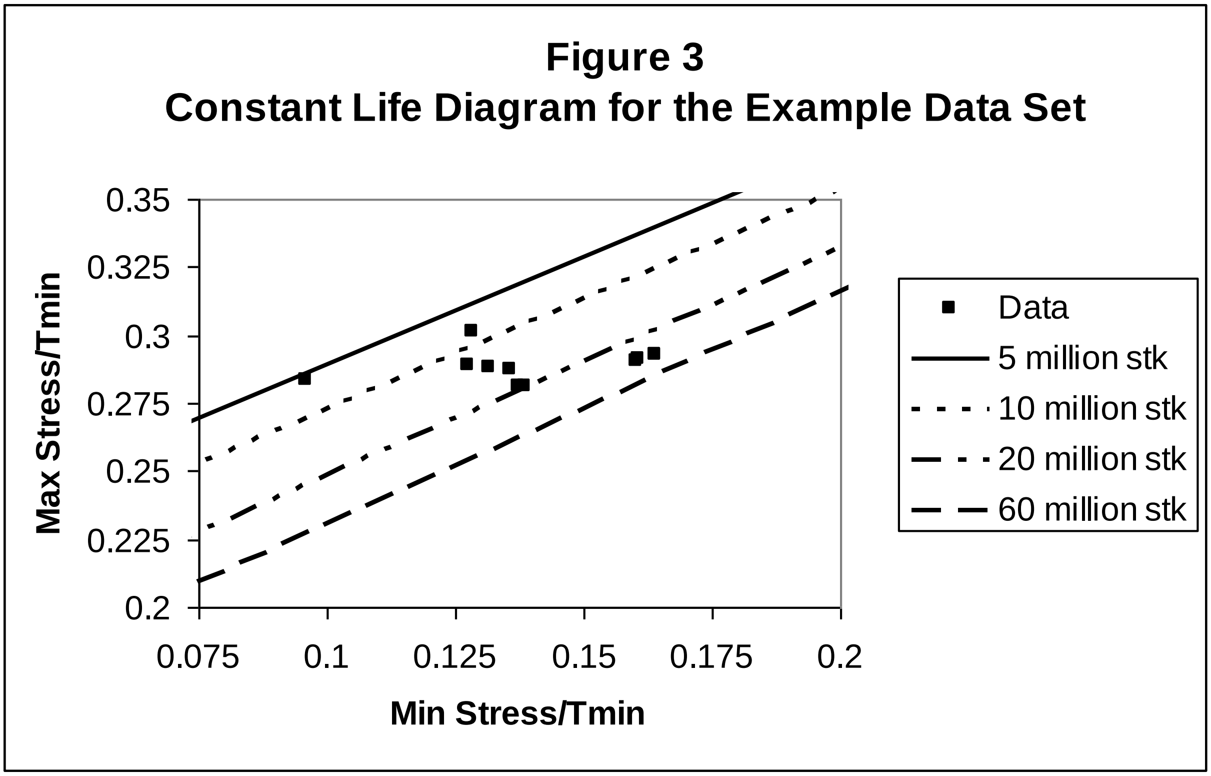


Figure 2
API Modified Goodman Diagram
0.6
0.5
0.4
0.3
0.2
0.1
0
max stress/Tmin
0
0.2
0.4
0.6
min stress/Tmin
Max Stress
Min Stress



Number of cycles to failure (millions)	Avg Max Stress psi	Smax/Tmin	Avg Min Stress psi	Smin/Tmin	R Smin/Smax	Avg Smean psi
7.366	34,640	0.301	14,751	0.128	0.43	24,696
13.627	33,027	0.287	15,605	0.136	0.47	24,316
20.75	32,379	0.282	15,944	0.139	0.49	24,162
24.279	32,350	0.281	15,787	0.137	0.49	24,069
5.748	32,586	0.283	11,034	0.096	0.34	21,810
22.362	33,232	0.289	14,654	0.127	0.44	23,943
27.186	33,157	0.288	15,134	0.132	0.46	24,146
46.777	33,444	0.291	18,426	0.160	0.55	25,935
47.281	33,457	0.291	18,455	0.160	0.55	25,956
55.336	33,654	0.293	18,848	0.164	0.56	26,251
55.822	33,654	0.293	18,868	0.164	0.56	26,261
Tmin = 115,000 psi						

Table 1
Example Data Set