MODIFYING THE MODIFIED GOODMAN DIAGRAM (MGD)

Norman W. Hein, Jr.
Norris Production Solutions (NPS) & Norris/AOT Operating Companies

ABSTRACT

The API RP 11BR Modified Goodman Diagram (MGD) has been used since the 1960s to establish the load range and maximum allowable load/stress range that should be applied to the various grades of sucker rods. Presentations in the 90s and subsequent recent work on fatigue testing sucker rods have shown the conservative nature of this recommended practice. This paper will provide a summary of the development history for the MGD, a summary history of sucker rod fatigue testing, along with discussing the potential industry modifications that are being considered to increase the maximum allowable load/stress for API sucker rod grades.

BACKGROUND

The industry, through the API Committee on Standardization of Oilfield Equipment (CSOEM) is required to review, reaffirm, modify or withdraw their standards typically on a 5 year cycle. While the latest edition of API Standards on sucker rod related equipment was published in May 2010[1], the latest edition of the API Recommended Practice 11BR was published in August 2008. Thus, two years ago, a Task Group (TG) was formed under API Subcommittee 11 responsible for Field Operating Equipment, to start the review process.

There was an extensive review and recommendations were made that the RP needed to be changed to reflect all the equipment and Annexes listed in Spec 11B. This would then have the formats similar and equipment in a specific Annex of the specification would have installation, operation, inspection, and repair information described in the RP.

During this review, a number of recommendations were made to discuss the use of other equipment than was currently listed in the Spec. Examples of these additions included high strength sucker rod grades, high strength couplings, sucker rod blow out preventers, polished rod liners, alternate sinker bar thread form, Based on the discussion and the wide spread industry need, it was then realized that a parallel effort had to be made to add this new equipment also in the Spec. So there was a new Task Group also charged under API SC 11 to review and revise API Spec 11B.

This paper will discuss the changes made to adopt high strength sucker rods and couplings along with a discussion on recommendations on how the industry should consider designing rod strings when this equipment is used. Further, the impact on adopting high strength rods brought to light the current industry practices for the designing rod strings using the existing API rod grades and on potential changes to increase the maximum allowable due to the very conservative basis of the design limitations set in the 1960s.

DISCUSSION

Table 1 shows a draft of the current recommendations for the addition of the industry's typical special high strength rod grades. These are called a variety of names based on the individual manufacturer, but all of these extend the tensile strength of the API D grade rods from 115 to 140 ksi to 140 to 150 ksi. According to the various manufacturers, all of the different types of the normally processed, high strength rods can be divided into either a specified alloy grade (AISI grade 41XX) or into a special alloy grade where the composition has a minimum of nickel, chromium and molybdenum that totals greater than 1.15 weight percent.
The table shows these two high strength rods as eight HA or HS, respectively. The other requirements for color coding and the mechanical properties are also provided in this table.

Table II shows the current draft changes for couplings. The special high strength couplings that should be considered for use with the special high strength rods are being proposed so that the couplings retain adequate strength and have similar design ratios for the cross sectional areas versus the rod body cross section area that exists for the current API T grade coupling.

During the review of the requirements for the high strength couplings, it was realized that the past reference to coupling grades was not appropriate since the base material was consistently required and the changes to the thickness or the addition of a spray metal coating did not change the base steel grade. However, there were no specific requirements for the type of steel or requirements on mechanical properties other than meeting a minimum tensile strength of 95 ksi. Additionally, it was recognized that many did not interpret the current hardness guide lines in the API spec and thought that the 56 to 62 HRA were actual limitations on the strength.

The new spec is currently being drafted so that there will be two grades of coupling T and H for the current, normal T and the new high strength H. Associated with each grade are different grades of steels typically used so that C for carbon, A for alloy and S for special alloy compositions and related markings will be incorporated in the spec. Further, specific ranges of mechanical properties for the T and H grade will be required. The SM grade for spray metal coated T class coupling will be dropped but obtaining spray metal coated couplings will still be possible as shown in the marking requirements. Also, the normal, full sized wall thickness along with slim hole wall thicknesses will still be available.

During discussion in the TG for 11BR, the question arose on what should be the maximum allowable design stress for the HA and HS rod grades. Since most manufacturers limited the allowable strength to the tensile strength (T) divided by 2.8, it was decided to use this as minimum allowable strength in the RP standard. So, assuming the minimum tensile of 140,000 psi is used for the rod grade, then at the zero minimum load or stress in the API RP Modified Goodman Diagram (MGD) the max allowable stress would be (140,000/2.8) = 50,000 psi. This has been the typical maximum allowable from most manufacturers for the special high strength rods for a very long time.

Adopting the T/2.8 then brought up the question why the normal, existing API grades are still using the T/4 that had been adopted as the industry practice since the 1960s when the Modified Goodman Diagram was developed. A brief history of the development of the original Goodman Diagram (Fig 1) and the modifications that were made by the industry has been published by Hein and Hermanson.[3] This paper, written in 1993, also discussed the very conservative nature of the Goodman Diagram and the MGD (Fig 2) since 30 years of fatigue testing from the original Goodman work has shown many improvements not only in the steel quality but in the factors that affect fatigue life. Additionally limited laboratory and field testing verified that allowable loads much greater than the MGD maximum allowable could be applied to API grade sucker rods and adequate fatigue life were observed, or there were no major increases in failures from applying higher than the T/4 stresses as recommended by the MGD.

A number of user, service company consultants and manufacturers on the TG for 11BR discussed their field histories of applying allowable loads with a Service Factor (SF), as described in the API RP 11BR, much greater than 1.0 which was tied to the T/4 maximum allowable load or stress. Some have had acceptable life with a 1.2 or 1.25 SF. Some have used 1.3 or 1.35 even in the new, deeper unconventional shale wells of the Eagle Ford reservoirs with adequate run life or no major increase in field failures. While a few operators provided their successful application of a SF greater than 1.0 for API grade rods, few ever published these results since most believed it provided them a production and business advantage to be able to use less expense steel rod grade and/or a lighter rod string and provide the necessary production goals without having an associated increase in operating expenses. There are some cases where failures actually decreased when the special high grade rods did not have adequate performance life due to highly applied stresses in a inadequate corrosion inhibited produced fluids. When this condition occurs, most special high strength rods will fail from corrosion fatigue and the origin is typically a small surface corrosion pit. However, when special alloy D grade rods (new API grade DS) were substituted and a SF greater than 1.0 applied, then the DS grade rods were acceptable in producing the wells and having acceptable run time. This was due to the lower strength, higher ductility and improved notch toughness from the DS vs. the HA or HA rods.

A comparison between the existing maximum allowable load or stress for the API rod grades at T/4 versus other potential higher allowable stress and the resulting SF for the new design limitation are shown in Table 3. The same allowable stress for the high strength rods is being recommended to be applied to all API grade rods from the API TG. Representative MGD for the new maximum allowable stresses for C and K grade rods is shown in Figure 3 for the minimum tensile condition of 90 ksi while the D grade rods new proposed MGD is shown in Figure 4.

Figure 5 provides a comparison for the Goodman Diagram max allowable stress with T/2 for the new HA and HS API grade rods. Additionally, the current recommended max allowable stress for T/2.8 for the field application of these new high strength rods is shown in Figure 5. Also shown are dashed lines for the historic allowable stress if case hardened sucker rods (EL grade) are used in a well.

A fatigue testing program has been on-going for many years by at least one sucker rod manufacturer. Figures 6 and 7 provide a comparison of the fatigue lives that have been average based on a minimum of three tests for each stress condition. These charts provide the resulting fatigue life for the special high strength rods and the D grade rods tested to-date. Note that the applied stress for these testing conditions was much greater than the recommended rod string design maximum allowable stress. For these tests, a T/2.5 or SF of approximately 1.6 was used. The testing that has been accomplished on high strength and API D grade rods is shown in Figure 8.

Figure 9 provides a summary of the new proposed additions and changes to the current MGD to reflect the addition of high strength rods to the API grades plus optimization of the existing API grades if the same maximum allowable stress of T/2.8 for all rod grades is used.

CONCLUSIONS AND RECOMMENDATIONS

1. New API Spec 11B is finally adding HA, HS and high strength couplings as well as other changes and new products to the next edition (published in late 2014 or early in 2015).
2. Industry needs to decide what is the recommended max allowable stress for the new additional rod grades
3. This is currently being proposed as T/2.8 for the API RP 11BR revisions.
4. Industry is currently considering changing the maximum allowable design stress for the current grades of API rods to (T/2.8) in the next editions for API RP 11BR (published late 2015)..
5. As with any new process and design change, it is highly recommended that an operator conducts appropriate pilot tests in their field
6. The major factors that affect sucker rod field performance life should be closely monitored and assured best operating conditions are applied if a pilot test is conducted to assure the rod grades with a SF greater than 1.0 will not prematurely fail due to poor operating practices. These factors include, as a minimum:
    - Good rod string design with downhole wellbore deviations properly included in the design stresses
    - Good corrosion protection and proper corrosion inhibition program is applied
    - Field operating practices prevent pounding fluid or almost complete pump fillage is obtained
    - Downhole equipment failure tracking and root caused analyses are performed to determine the causes and then how to prevent failures.

ACKNOWLEDGEMENTS

The author wishes to thank his company management for allowing this paper to be presented.

REFERENCES

1. API Spec 11B, “Specification for Sucker Rods, Polished Rods and Liners, Couplings, Sinker Bars, Polished Rod Clamps, Stuffing Boxes, and Pumping Tees,” 27^{th} edition, (With Errata 1, October 2010, Errata 2, February 2011), Washington, D.C., 05/01/2010.
2. API RP 11BR “Recommended Practice for the Care and Handling of Sucker Rods,” Ninth Edition, Washington, D.C., 08/02/2008.
3. Hein, Jr., N.W., and Hermanson, D.E., “A New Look at Sucker Rod Fatigue Life,” SPE 26558, ATCE SPE Houston, TX Oct 3-6, 1993.
4. Hein, Jr., N.W. and Eggert, D., “Steel Sucker Rod Fatigue Testing – Phase I Update,” SWPSC, Lubbock, paper #11, 2013.

Table 1- Draft changes to the next revision of API Spec 11B incorporating high strength rods

Color Code, Chemical Composition, and Mechanical Properties of Steel Sucker Rods and Pony Rods

API Grade	Color Code	Chemical Composition	Yield, minimum, 0.2% offset, psi (Mpa)	Tensile, minimum, psi (Mpa)	Tensile, maximum psi (Mpa)	Elongation, minimum, 8 inches %	Reduction of Area, minimum, %
C Carbon	White	AISI 10XX Series Steel [a] AISI 15XX Series Steel [a]	60,000 (414)	90,000 (620)	115,000 (793)	13	40
K Alloy	Blue	AISI 43XX Series Steel [a] AISI 46XX Series Steel [a]	60,000 (414)	90,000 (620)	115,000 (793)	13	40
DC Carbon	Brown	AISI 10XX Series Steel [a] AISI 15XX Series Steel [a]	85,000 (586)	115,000 (793)	140,000 (965)	10	40
DA Alloy	Yellow	AISI 41XX Series Steel [a]					
DS Special	Orange	Any chemical composition that contains a combination of nickel, chromium and molybdenum that totals a minimum of 1.15% alloying content					
HA Alloy	Green	AISI 41XX Series Steel [a]	115,000 (793)	140,000 (965)	155,000 (1068)	8	30
HS Special	Purple	Any chemical composition that contains a combination of nickel, chromium and molybdenum that totals a minimum of 1.15% alloying content					

[a] Or an equivalent international series number steel.

Table 2 - Draft changes for API Spec 11B incorporating high strength couplings

Table C 1. Class, grade, chemical composition, yield, tensile and marking requirements for steel couplings and subcouplings (DRAFT)

API Grade	API Coating Type	Product Marking	Chemical Composition (AISI Steel Series)[a]	Yield, 0.2 % Offset, Minimum psi (Mpa)	Tensile, Minimum psi (Mpa)	Tensile, Maximum psi (Mpa)
Class T Couplings and Sub-couplings						
TC (carbon)	None	TC	10XX or 15XX	60,000 (450)	95,000 (655)	120,000 (862)
	Spray Metal	TCS				
TA (alloy)	None	TA	41XX or 51XX or 86XX	60,000 (450)	95,000 (655)	120,000 (862)
	Spray Metal	TAS				
TS (special alloy)	None	TS	Any chemical composition that contains a combination of nickel, chromium, and molybdenum that total a minimum of 1.15% alloying content	60,000 (450)	95,000 (655)	120,000 (862)
	Spray Metal	TSS				
Class H (High Strength) Couplings and Sub-Couplings						
HA (alloy)	None	HA	41XX or 51XX or 86XX	80,000 (550)	120,000 (862)	150,000 (1034)
	Spray Metal	HAS				
HS (special alloy)	None	HS	Any chemical composition that contains a combination of nickel, chromium, and molybdenum that total a minimum of 1.15% alloying content	80,000 (550)	120,000 (862)	150,000 (1034)
	Spray Metal	HSS				

[a] Or an equivalent international series number steel

Table 3 - Comparison of Maximum Allowable Design Stresses, Resulting Stress Condition and Related SF

Max Allowable Stress Factor	C & K Grade (Min T = 90 KSI)	D Grade (Min T = 115 KSI)	Relative SF New Allowable/(T/F) stress
T/4	22.5	28.75	1.0
T/3.5	25.7	32.9	1.14
T/3	30.0	38.3	1.33
T/2.8	32.1	4101	1.43
T/2.5	36.0	46.0	1.6
T/2	45.0	57.5	2.0

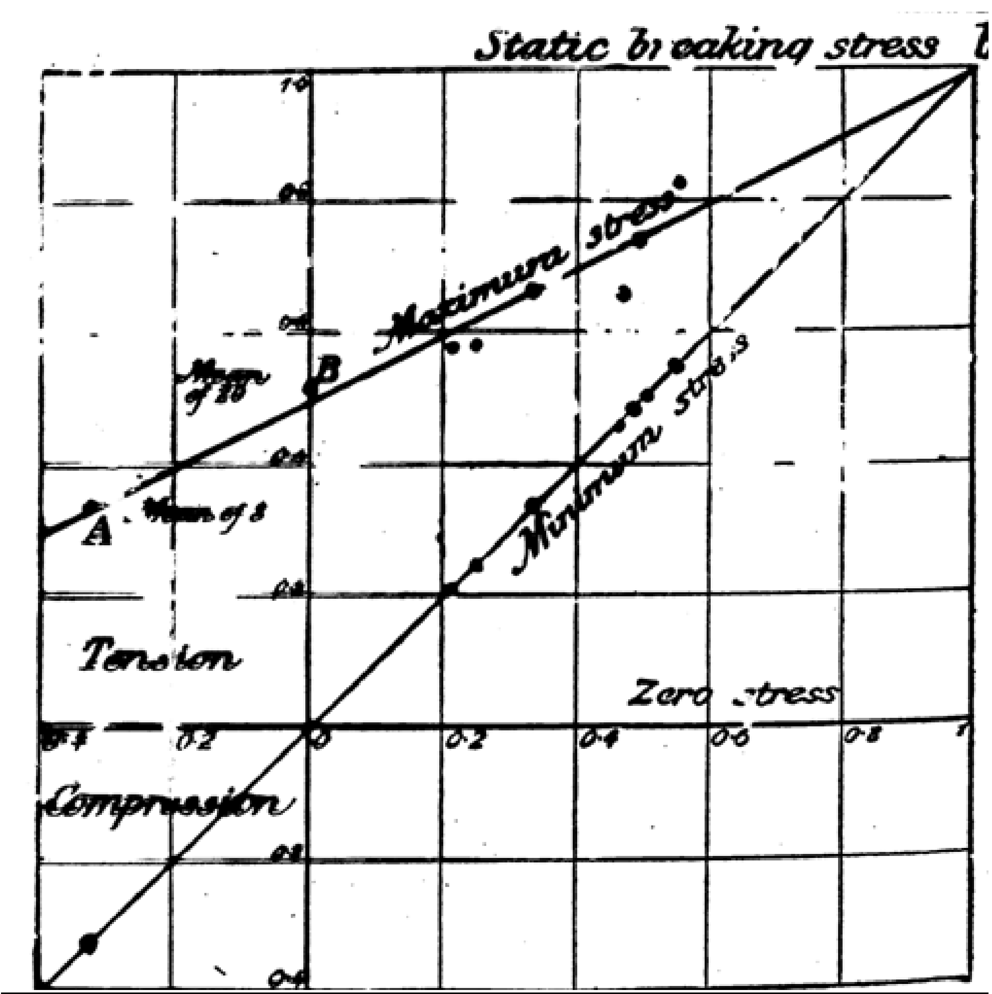

Figure 1 - Original Goodman Diagram from rotary bend fatigue in 1926

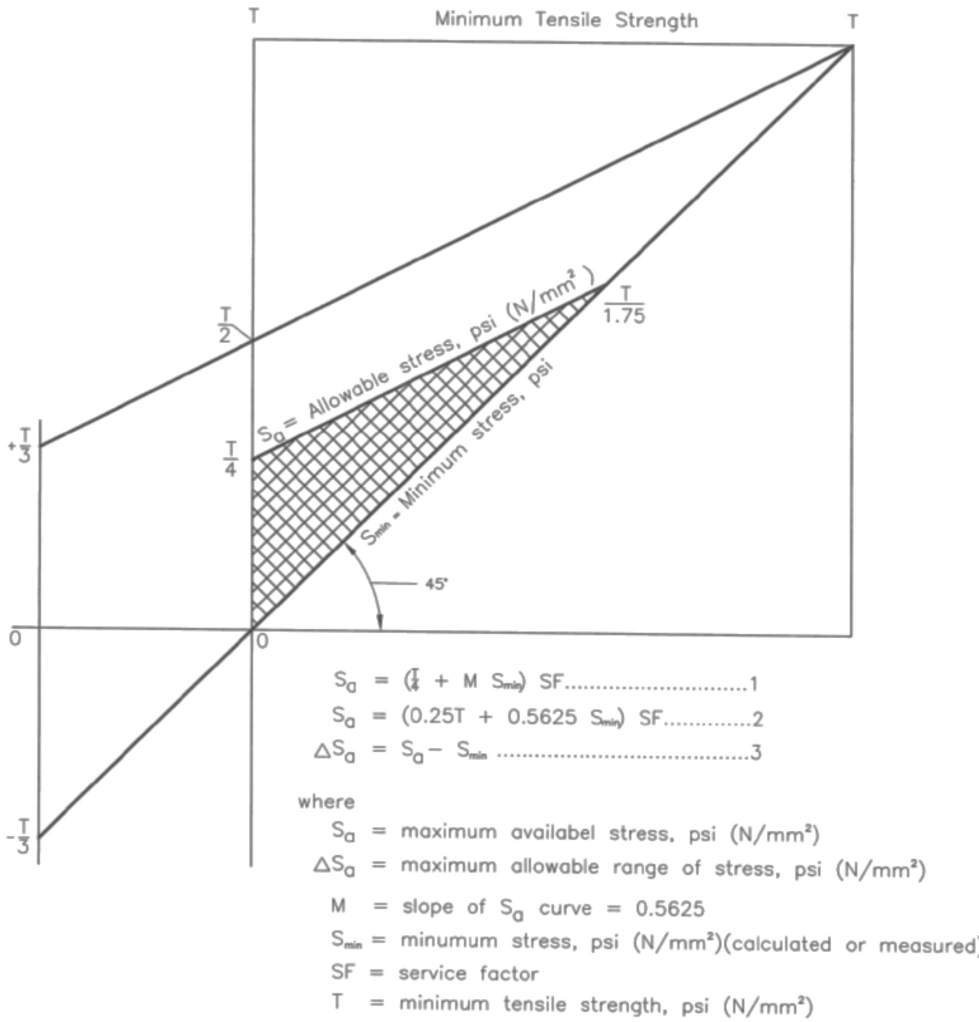

Figure 2 - API RP 11BR Modified Goodman Diagram (MGD) with T/4 Max Allowable Stress

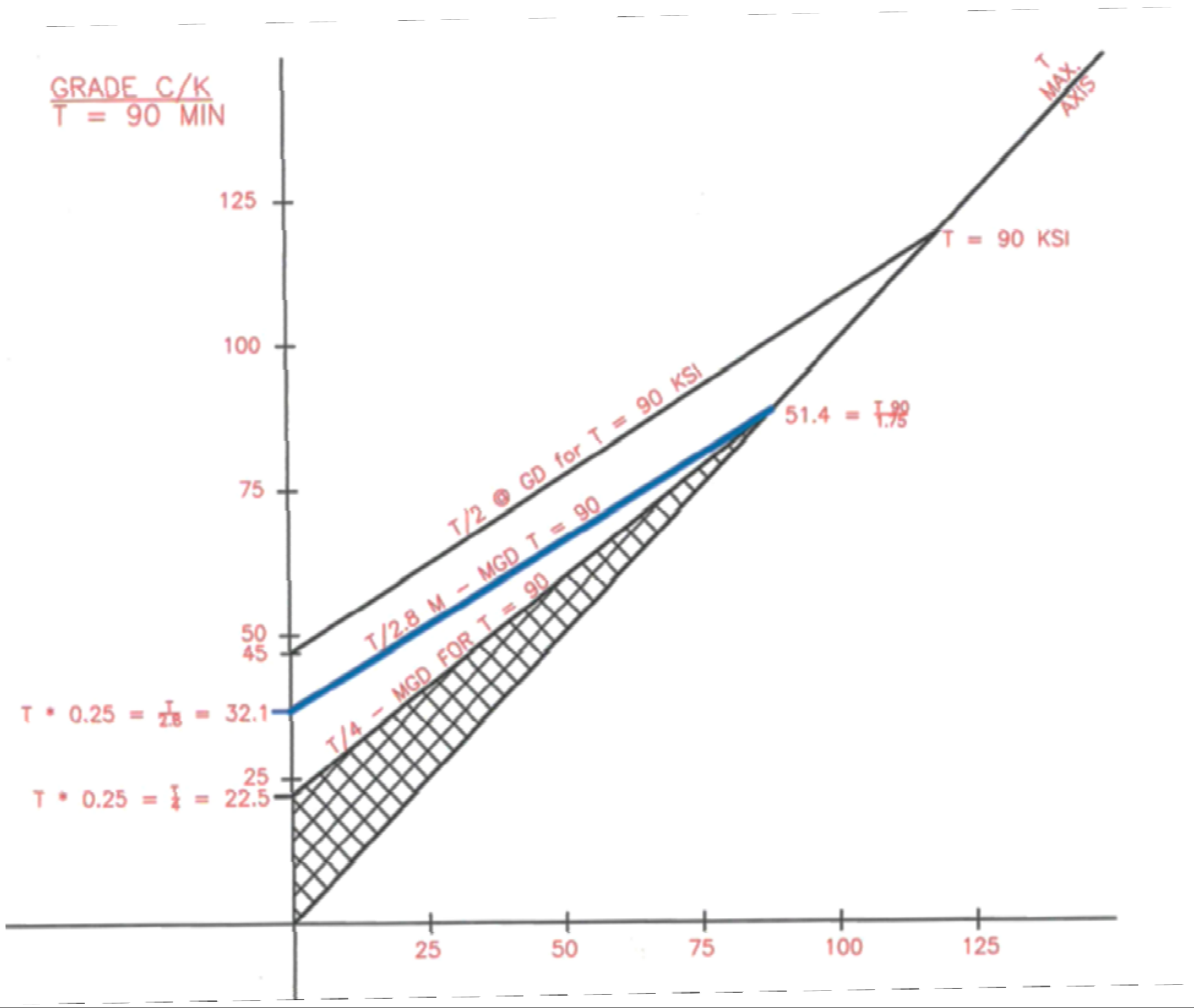

Figure 3 - Comparison between original Goodman, MGD, and proposed new API Modified MGD for C & K grade rods

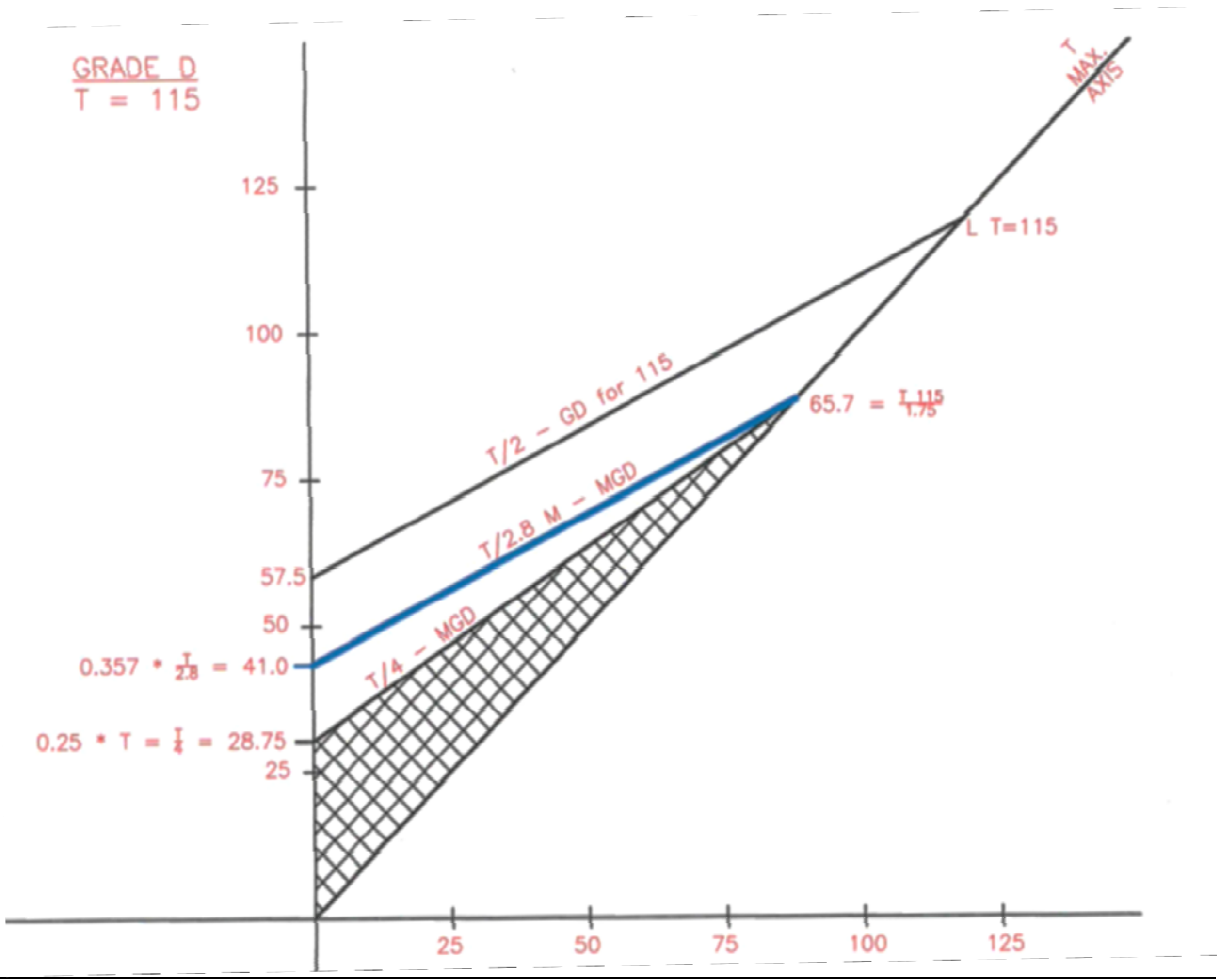

Figure 4 - Comparison between original Goodman, API MDG and new proposed API Modified – MDG for D grade rods

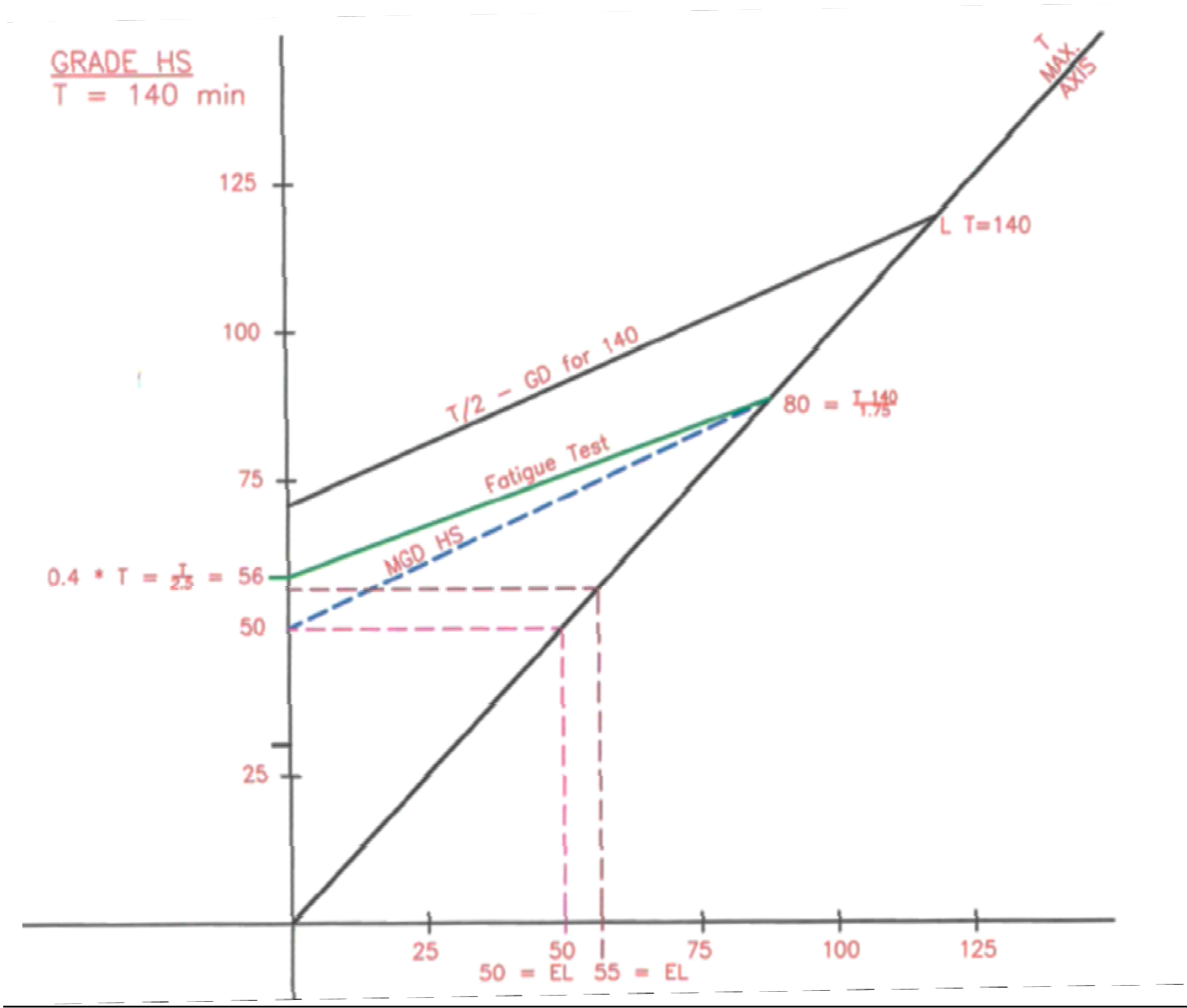

Figure 5 - Comparison between original Goodman, MGD for HA/HS rods, and other special high strength case hardened rods

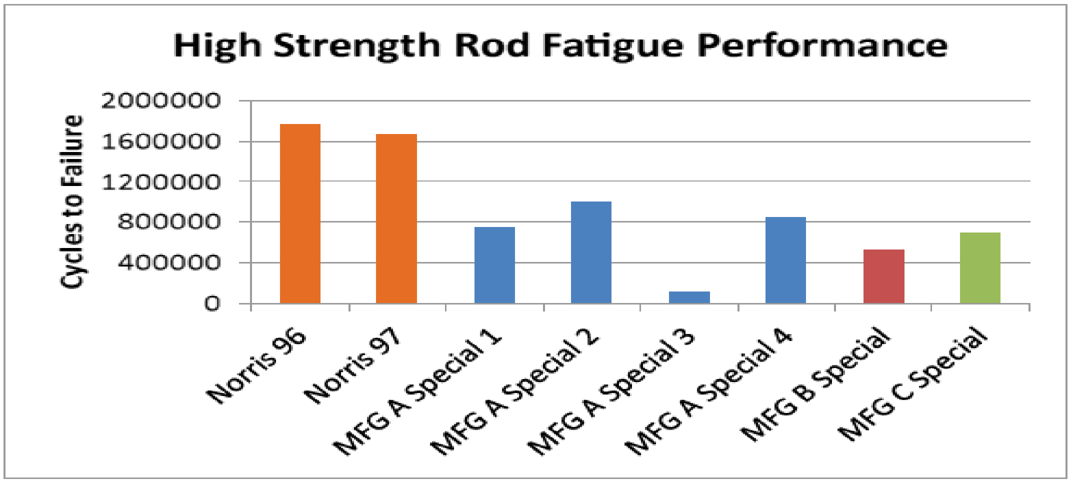

Figure 6 - Fatigue graph summary for special high strength rods (ref 4)

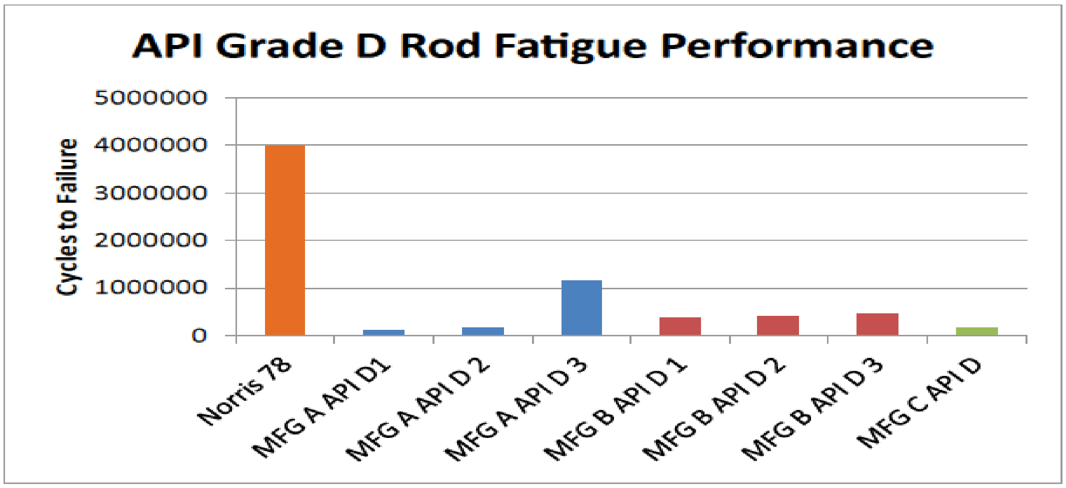

Figure 7 - Fatigue graph summary for and added D 78 fatigue life test data for API D grade rods (ref 4)

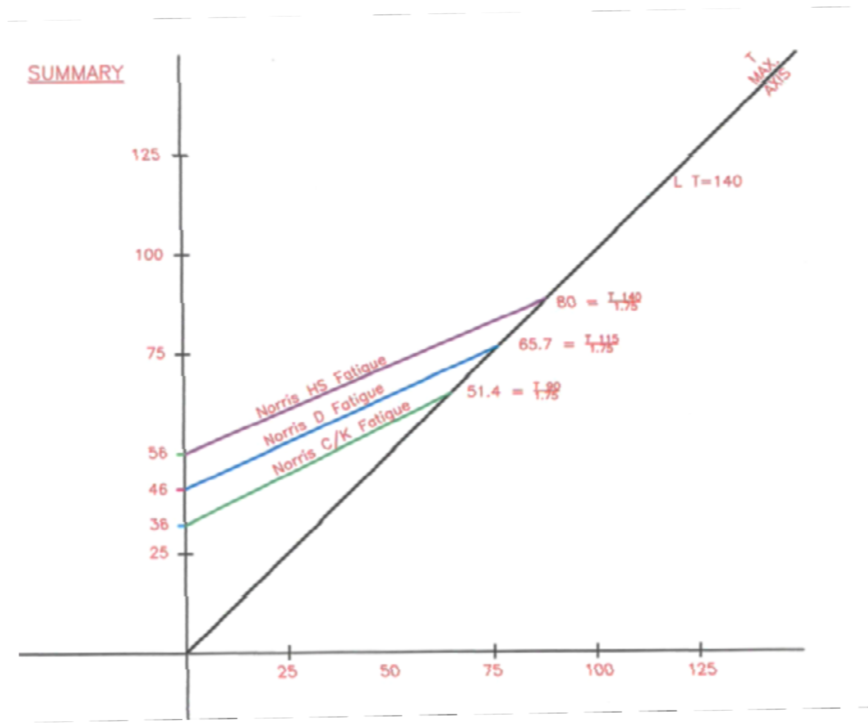

Figure 8 - Summary of rotary bending fatigue testing stresses for the current HS and D fatigue tests that have been conducted as well as future C & K proposed fatigue testing applied stresses.

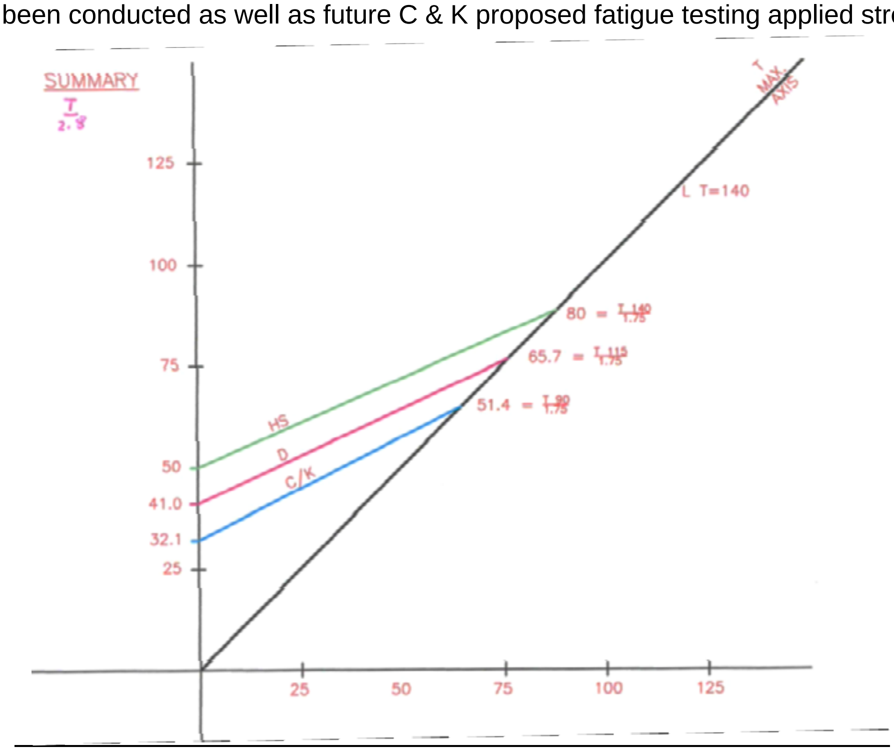

Figure 9 - Comparison summary of all grades of API including new HA/HS rods with T/2.8 as design maximum allowable stress draft recommendations.