SUPER HI-STRENGTH SUCKER RODS

E.W. METTERS
OILWELL Division of
United States Steel Corporation

During the early 1960's much work was done with compressive prestressing of material used in oilfield equipment to overcome fatigue problems which had plagued the industry for years.

The API adopted the undercut-thread sucker rod pin design to overcome pin failures which had become a serious problem as sucker rod loads increased. The undercut pin design made it possible to produce the threads by rolling, with further increases in pin fatigue strength.

Microhardness profiles were run on these new pins, and it was found that on a typical API Class C normalized sucker rod, the hardness at the thread root had increased significantly.

At a depth of about 0.001 of an inch from the surface of the thread root, the hardness value was approximately 34 on the Rockwell C scale; at 0.002 it was about 30.3 Rc: at 0.004 it was about 25.5 Rc and so on to a depth of about 0.012 of an inch where it leveled out at a Brinell hardness of about 185. Photomicrographs proved some of the success of the new API pin could be attributed to the compressive prestress of the thread root.

Shortly after the introduction of the improved pin design it was found that the breakage problem had been pretty well eliminated in the sucker rod pins but increased breakage was appearing in the sucker rod coupling. In 1964 a new method of forming the threads in a sucker rod coupling was developed. Microhardness profiles and photomicrographs confirmed this new manufacturing procedure developed compressive prestress at the thread roots very similar to the profiles of the roll-threaded sucker rod pin. This time, however, the only change was in the threading process. Tests indicated couplings manufactured with the new technique were 50% stronger than couplings manufactured using conventional taps. The prestressing of the thread root was the reason for the increase in work capability of the coupling.

During this period much time and effort were put forth endeavoring to find a means of using this knowledge to increase sucker rod strengths by prestressing the surface of the rod.

One of the early developments along this line of thinking was a rod which was shot-peened. Rods which had been shot-peened showed improvement in fatigue resistance ranging from 1.6% at a load ratio of 60% to 12.8% with a load ratio of 20%.

Induction heat-treating equipment was developed to increase and control case thickness in the manufacture of test pony rods in an effort to establish the optimum depth of compressive prestress a sucker rod should have in order to increase its load-carrying ability and at the same time improve its fatigue resistance.

The selection of material for the original test proved to be a good one. Lab tests indicated the selection of Grade 1036 would do the best job.

In August of 1964, ⅝-in. test sample pony rods were sent to the field for installation in oil wells. These samples had case depths of 0.045 in., and the case was run out next to the wrench square. All samples had been quenched and tempered prior to induction hardening. Of some 15 test rods sent to the field, no test rod broke in the induction-hardened portion. There were two pin breaks, one due to improper torque makeup and one due to corrosion. The case-hardened portions exhibited an apparent improvement in corrosion resistance, while the unhardened wrench squares appeared to have been preferentially attacked.

In all the test wells the ⅝-in. test pony rods were installed above the ⅞-in. portion of the rod strings. As mentioned before there were no breaks in the rod body of any of the test rods, while in every well there were failures in the low stressed, larger conventional rods located below the test rods.

Most notable was the 34-months' service of a ⅝-in. rod where 13 failures occurred in the larger rods below the test rod. This pony rod was still serviceable when removed from the well.

From the test it was determined that some form of treatment would be necessary on the upset portion of the sucker rod and that a superior rod could be manufactured without heat treatment prior to induction hardening. This meant two high-strength sucker rods of different capacities could be manufactured using this new process.

After more than two years of testing various test strings of full length induction-hardened rods, it was possible to set design specifications. Final design called for a rod capable of 40,000 psi working stress level and one of 50,000 psi level.

Following forging operations the pin ends of the 40-KSI rods are liquid-quenched and tempered. Then the rod is induction-heated from shoulder to shoulder to a controlled depth and liquid-quenched. The rod is then shot-blasted and the pin ends machined with API undercut pins and rolled threads.

The 50-KSI rod manufacturing procedures differ in several ways. After end-forging, the rod is completely heat-treated, liquid-quenched and tempered for greater core strength. Additional strength is developed by hot-stretching and strain-aging. The rod is then induction-heated from shoulder to shoulder to a controlled depth and liquid-quenched. This rod is then shot-peened to further increase its compressive prestress. Finally the pin ends are machined to API specifications and the threads rolled on.

After the design levels had been established, it was recognized the wrench square area as specified by the API for the ⅞-in. rod was not capable of safely handling the loads.

As set up by the API, the wrench square areas are 1.000 in.^{2} for ¾-in., 1.000 in.^{2} for ⅞-in. and 1.724 in.^{2} for 1-in. rods. The ratio of these to the rod body is 2.26 for ¾-in., 1.66 for ⅞-in., and 2.2 for 1-in. To make a more balanced sucker rod design, the ⅞-in. wrench square was increased from 1 in. to 1⅛ in. across the flats giving an area of 1.266 in. and a ratio to the body of the rod of 2.11 which is much more in line with the other sizes.

The ⅞-in. rod's wrench square area, therefore, exceeds the API dimensional specification for sucker rods in order to provide a balanced high-strength rod design.

If it had not been for the breakthrough in coupling threading technique in 1964, the super hi-strength rod could not be used today because conventionally threaded couplings cannot match the strength of these new rods. Even with the additional strength in properly threaded couplings, it is not advisable to run slim-hole couplings at these high stress levels.

It is suggested that the ratio of coupling area to rod body area be no less than 2.68 for ¾-in., 2.43 for ⅞-in. and 2.09 for 1-in. rods. Field testing has also shown the API Class T thru-hard coupling to be much more susceptible to corrosion when subjected to the high stress levels of the "ELECTRA" Series Rods. This is why spray-coated couplings are recommended for use with these rods. If corrosion presents no problem, the Class T coupling is perfectly acceptable.

Caution should be used when purchasing replacement couplings for these hi-strength rods. Be certain the coupling is threaded using a process which will impart adequate compressive prestress in the thread roots to overcome the stress rising notch effect of the thread. Unless this precaution is taken, premature failures in the couplings can be anticipated. All couplings used to date on the "ELECTRA" rods have been quenched and tempered after metal-spraying and before threading. This process gives the coupling higher than normal impact qualities. The additional heat treatment may not be necessary, but couplings manufactured in this manner will perform on the super hi-strength "ELECTRA" II rods.

Having discussed the merits of compressive prestress, consider the details of the hi-strength rod construction.

Due to the induction heat treating and quenching process, the rod outer case is in extreme compression, as high as 125,000 psi. This strata of compression is anywhere from 0.065 in. to 0.080 in. thick depending on the rod size. Preferably this will range from 5-8% of the rod diameter; however, it can range from 3-15% of the rod diameter. A case depth of less than 3% is inadequate; while a case depth of greater than 15% makes the rod too brittle.

The compressive prestress blends into the core of the rod which for a distance will be in tension. Under a full stress load as in the 50,000-psi rod, the case compression will still be in the neighborhood of 60,000 psi.

Since the outer case of the rod is never subjected to tensile stresses, stress fatigue will not occur. Therefore, in designing rod strings, the load range (minimum to maximum) can be ignored since this rule is only necessary for determining fatigue limits. To date there have been no typical fatigue failures in this type rod; if a rod fails it is caused by something other than fatigue.

Hydrogen sulfide is present to some degree in most oil wells and causes hydrogen embrittlement. It is known that sensitivity of carbon steel to hydrogen embrittlement increases as the hardness and strength of the steel are increased. Hydrogen embrittlement lowers the ability of steel to withstand tensile loads. What has been done is to provide an improved rod and processing method which significantly increases fatigue resistance, yet does not increase its susceptibility to failure from other causes such as hydrogen embrittlement.

The microstructure in the case on these rods is substantially martensitic with possibly a small amount of retained austenite but containing no free ferrite. The single-phase case will tend to tolerate corrosion better than the conventional two-phase structure of iron carbide and ferrite. The single-phase structure will not be attacked by corrosion as readily as the two-phase structure since it is free of ferrite. Also, the compressive residual stresses will improve resistance to failure caused by hydrogen embrittlement. The hardness of the case will fall within a range of 475 to 650 Brinell.

When the rods are in service, the stress pattern attained by rods made by these new production techniques lowers the net tensile stress at the surface which is the main cause of fatigue cracking. The substantially martensitic case is necessary to furnish the desired stress pattern without expensive alloys or expensive treatments such as nitriding or carburizing.

As already mentioned, the hardened surface of the rod might be expected to increase the sensitivity of the rod to hydrogen embrittlement which would lower its ability to withstand tensile loads. The manufacturing technique used overcomes this difficulty to a degree by supplying additional compressive stress at the rod surface. Thus, when a rod operates within a well, the surface carries a net compressive load. Fracturing normally originates on the rod surface but fractures cannot begin in the absence of tensile loads to cause them.

To manufacture the super hi-strength rod known as the "ELECTRA" II, shot-peening in combination with the induction hardening is employed to achieve the 50,000 psi working stress capability.

Actual performance of the super hi-strength rods has been exceptional.

In Well No. F327P there was a history of frequent rod breaks using a 2-in. pump set at 7990 ft with API No. 96 rod string. Within a year's operation failures started occurring. The No. 96 string was replaced with an API No. 86 string of "ELECTRA" II's on January 19, 1971. Total rod weight was reduced by 15%, the peak polished rod load was reduced by 9%, the peak sucker rod stress was increased by 15% and the average reducer horsepower was reduced by 6%. Even with an increase of 15% in the stress level, this string has operated for 704 days without failure. Measured load on this string is 33,800 lb with the peak polished rod load giving a stress on the top rod of 43,057 psi.

In another well, VL & W No. 51, a change was made for a different reason. In this case using an API No. 86 rod combination, the customer was able to produce the well with relatively few failures; however, the surface equipment was overloaded. It was determined that an API No. 76 rod design using "ELECTRA" II's would be adequate to produce the well without overloading the surface equipment. The design indicated peak rod stress would be in the area of 46,000 psi. A string of 50,000-psi rods was run into the well on February 25, 1971. Total rod weight was reduced 16%, and the peak torque and average reducer horsepower were reduced by 8%. The actual measured polished rod load on this well is 27,251 lb making the stress level of the top rod 45,343 psi. To date this string has operated for 668 days without a failure. However, there have been three ⅞-in. coupling failures, one polished rod coupling failure, as well as a polished rod failure. Two ¾-in. rods were replaced after pins were damaged on two rods while the well was being serviced.

Another test well, Hathaway No. 25, was selected due to an extreme load range. This particular well uses a double displacement pump and is operated with an 86-in. stroke unit operating at 18.5 SPM giving an acceleration factor of 0.417. After installation of 40,000-psi rods on January 25, 1971, the well was weighed and showed a peak polished rod load of 15,520 lb and a minimum load of 500 lb. A non-uniform taper was used in this well so the ¾-in. section would be operated at a higher than normal stress level. It is calculated the top portion of the ¾-in. section is operating at 31,000-psi peak to a minimum of 679 psi. To date there have been two pin failures, both due to improper makeup.

Another spectacular performance has occurred in the Moss Unit No. 10-6 Well. Dynamometer measurements showed a peak load of 32,360 psi and a ratio of 19%. Prior history showed this well using two new strings in a period of one year. At this writing the "ELECTRA" rods have been in service for 798 days and are still going strong with no reports of failure.

Probably the most outstanding test was on the Vess Unit No. 249. The previous rod string consisted of an API No. 97 combination. An API No. 86 combination of 40,000-psi rods was run into the well on June 10, 1971. This well had previously averaged two failures per week. Now after 564 days there have been no failures. The rods are operating at 36,000 psi with a ratio of 25%.

There are now operating over 2 million ft of "ELECTRA" I's and II's in the United States and Canada. Failures have been minimal. There have been about 24 body breaks caused mostly by mechanical damage such as nicks or bending. At this time four complete strings have been removed from wells, one of which was due to the rods being overstressed.

As previously stated, the design goal on these rods was to make them less susceptible to corrosion. It is felt this goal has been achieved.

The product is not entirely immune to corrosion damage but it is felt that it will tolerate corrosion. Experience has shown that no failure will occur until such time as the corrosion has penetrated the outer case of the rod.

At this time there are numerous alternate rod-type tests taking place in various parts of the country. Since this is the type of test which takes time, no conclusions have been reached as yet; but indications are that an inhibition program which was found to be successful previously will be adequate for the hi-strength rods even though the rods will be working at a much higher stress level.

The corrosion that has been encountered so far does not seem to be affected by the stress level at which the rod was operating. Presently, it does not appear that using a service factor against the rod's rating will be beneficial in extending the life of the rod; and since no fatigue failures have ever occurred, the ratings of the rods are constant without any derating being required for the range of load.

Benefits of using the super hi-strength "ELECTRA" Series Rod are great. Based on API Bulletin No. 11L3, Table 1 shows two examples of how the high-strength rods can benefit the user.

TABLE 1

Example 1: 3500 ft, 1500 BPD

Rod No.	Pump Dia.	Stroke	SPM	PPRL	Stress	Peak Torque
76	2.50	192	11.4	19,734	32,836	902,000
86	2.50	192	13.5	22,211	28,294	1,074,000
96	2.50	192	11.1	24,889	25,039	1,101,000
97	2.50	192	11.1	25,191	25,343	1,119,000

Example 2: 10,500 ft, 300 BPD

Rod No.	Pump Dia.	Stroke	SPM	PPRL	Stress	Peak Torque
86	1.50	168	8.6	32,805	41,790	772,000
96	1.50	168	8.7	36,413	36,633	809,000
97	1.50	168	8.2	39,473	39,711	887,000
98	1.50	168	7.8	43,817	44,081	1,034,000

In example 1, Table 1, the high-strength rod could be used to reduce the unit reducer size.

Under these conditions the selection of the No. 86 rod combination would allow the use of not only a smaller gear reducer but also a structure of lesser capacity.

By including the new "ELECTRA" Series Rods in the design, it is possible to upgrade current surface equipment; or, in the case of a new installation, smaller surface equipment can be used.

Figure 1 shows the maximum allowable stress for rods having a minimum tensile strength of 115,000 psi as it relates to the stress range S_{MIN}/S_A. Also, in Fig. 1 will be found horizontal lines designating the predicted performance of the new-type rods at constant stress capabilities throughout their respective ratings of 40,000 to 50,000 psi regardless of the stress range.

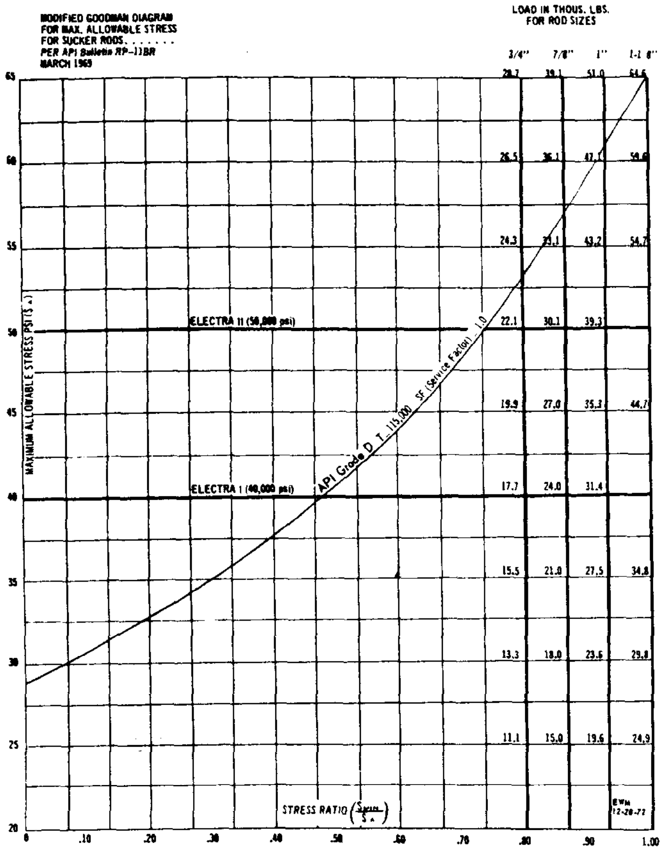

FIGURE 1

A random selection of operating conditions from API Bulletin No. 11L3 showed an average operating stress range, or load ratio, of .2997. Referring to Fig. 1 over a stress ratio of .30, we find an API Grade D rod would have a theoretical stress capability of 35,000 psi; while the "ELECTRA" I rod would still be capable of 40,000 psi and the "ELECTRA" II rod would still be 50,000 psi. This stress is converted to pounds on the right side of the table. In this particular instance the ⅞-in. API Grade D rod would be capable of 21,000 lb while the ¾-in. "ELECTRA" II rod would be capable of 22,100 lb, the 1-in. "D" rod could carry 27,000 lb, the ⅞-in. "ELECTRA" II could carry 30,100 lb; and a 1⅛-in. "D" rod has a capacity at a stress ratio of 0.30 of 34,800 while the 1-in. "ELECTRA" II has a capacity of 39,300 lb. If these factors are taken into consideration when designing rod installations, smaller rods can be used. With minor adjustments to the strokes per minute of the pumping unit, the same volumes can be lifted and, in many cases, sizeable savings can be realized in the purchase of the capital equipment. On the same basis, old wells and equipment can be upgraded if necessary to increase the depth setting of a pump in a given well or to reduce the load on the surface equipment.

Due to the construction of the super hi-strength "ELECTRA" Series Rods, there are some ground rules which must be followed in handling and installing the rods. Consistant performance at high working stresses require adherence to all instructions contained in API Bulletin No. RP-11BR, *Recommended Practice for Care and Handling of Sucker Rods.* Installation instructions for proper makeup are listed in Table 2 below and must be followed.

TABLE 2—SIZES AND SPECIFICATIONS

Rod Size	Coupling	Coupling Box OD*	Wrench Square	Displacement for New Rods (from Hand Tight Position) For proper Makeup Min.	Max.	Recommended Makeup Torque Ft.-Lbs. (for Clean Lubricated Joint)
¾"	Grade C (Co-Hard)	1⅝"	API-1"	9/32"	11/32"	385
⅞"	Grade C (Co-Hard)	1-13/16"	Non-API 1⅛" to match sucker rod strength	11/32"	12/32"	572
1"	Grade C (Co-Hard)	2" 2-3/16"	API-1¼"	14/32"	16/32"	880

* Other OD's available on request

BIBLIOGRAPHY

1. API Sucker Rod System Pumping Design Book, Bulletin 11L3.
2. API Bulletin RP11BR, 5th Edition, March, 1969, Recommended Practice for Care and Handling of Sucker Rods.

3. API Supplement 1 to API RP11L, First Edition, January, 1970, Recommended Practice for Design Calculations for Sucker Rod Pumping Systems (Conventional Units).

ACKNOWLEDGMENT

The author wishes to thank the OILWELL Division, United States Steel Corporation, for permission to publish this paper. Appreciation is expressed to the development engineers, Messrs. F.L. Current of the OILWELL Division Imperial Works and Allen Stormer of the OILWELL Division Garland Works for their assistance in the preparation of this paper.

The process of manufacturing the rod described in this paper is covered by U.S. Patent No. 3,489,620.