Case Study

Performance comparison of BOR-1Cr borided tubing versus conventional 1Cr L80 tubing for wear, erosion and corrosion resistance operating together in a rod pumped oil well

Comparison of EMI scanning results to 24 arm caliper measurements on borided tubing

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Case Study Definition:

The goal of this case study will be to compare the performance of two sets of OCTG tubing operating in the same well. This will be a simple head to head comparison of borided BOR-1Cr joints to conventional L80 joints both operating in the same well installed next to one another. Both sets of tubing will be operating in the same well and same operating conditions, however it should be noted that the borided joints being closer to the pump will experience higher operating temperatures (increased corrosion rates) along with increased rod buckling and closer proximity to pump discharges and turbulent flow which will all put the borided tubing at a distinct disadvantage compared to the conventional 1Cr L80 joints above them.

This well will be operated until failure and then both sets of tubes will be inspected and measured to quantify how much wall thickness loss has occurred in each tube during the normal operation of the well. The performance of each set will be calculated and compared to determine the benefit of using borided tubing to mitigate wall thickness loss due to sucker rod wear, pump discharge erosion and corrosion in real world operating conditions.

Several operators have also inquired about feasibility of EMI scanning borided tubing. In this case study, the results from a 24 arm caliper run will be compared to EMI scanning results on twenty borided tubes to establish how well the EMI scanning results correlate to the 24 arm caliper results. We assume that a mechanical measurement technique such as 24 arm caliper should be accurate. EMI scanning is believed to be not as accurate on borided tubing where subsurface iron-boride compounds that are formed can alter the electrical/magnetic properties of the tubing material.

Background of case study:

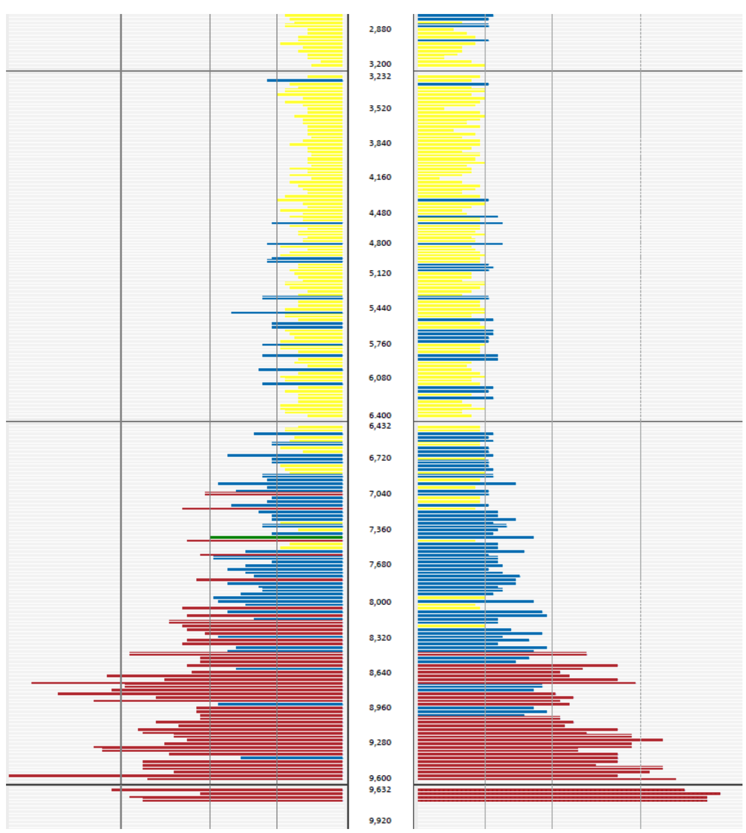
Prior to this case study, Bluewater had not yet performed a true head to head comparison of borided tubing to conventional tubing inside of an actual oil well with real world operating conditions. Various laboratory tests that simulate downhole wear and corrosion have been used to characterize the performance of borided steel compared to untreated steel, but these types of laboratory tests aren't the same as running actual tubes in a real well and seeing how they perform. Some of the laboratory tests that has been performed prior to this case study are described below and details of these tests are available upon request.

Borided tubing is known to be extremely wear resistant and this has been demonstrated using standardized laboratory tests such as the ASTM G65 abrasive wear test. In this test, borided test coupons were demonstrated to have 19.5 times less material lost due to abrasion compared to standard untreated steel coupons of the same tubing material. Borided tubing is also known to be more corrosion resistant than standard tubing. Autoclave corrosion testing of borided and untreated steel coupons has demonstrated that borided steel corrodes at a slower rate compared to untreated steel coupons. To date, Bluewater has performed three autoclave corrosion tests of borided versus untreated steel in different environments. The results have ranged from borided steel having only lost 12 to 66 percent of the material mass due to corrosion pitting when compared to untreated steel. Evidence also exists that borided tubing is much more resistant to erosion from directed flows of liquids and sand impinging directly upon the tubing wall such as a pump discharge aimed at a tubing wall can create. However, all of these tests that have been used to demonstrate the effectiveness of borided tubing to mitigate wear, erosion and corrosion failures have been performed in laboratory settings and are not exactly indicative of real world downhole operating conditions.

Typical Use of Borided Tubing:

Borided tubing has been used by many operators around the world for many years now and it has been deemed to be highly effective in mitigating wear, erosion and corrosion failures. The Bakken shale region has been a large area of use for borided tubing inside the United States. In discussions with several engineers at major oil producing companies, it appears that many started out placing two borided joints directly above the pumps at the bottom of their wells as the first two joints are known to be the worst location in the tubing string where the majority of failures occurred prior to the use of borided tubing. These first two joints experience the highest corrosion rates where temperatures are the hottest along with it being the most severe area for rod buckling creating sucker rod on tubing wear. In addition to those issues, many pumps can discharge flows that impinge sideways against the tubing walls in the first two joints up from the pump which can lead to erosion and hole in tubing failures at these pump discharge locations and the pull rods of the pumps may not be guided as they need to clearance to enter the pump barrel. Some work has been done recently to turn the tubing at timed intervals to change where erosion is occurring on the tube surface along with redesigning the discharges to change the angle of the flows such that they won't erode the tubing nearly as fast. However, it is still common practice yet today to place at least two joints of borided tubing above ESP pumps and at least 6 joints above rod pumps to help mitigate wear and erosion failures from pump discharges and sucker rods.

A typical EMI scan shown below demonstrates that the most severe areas for wall thickness loss in tubing strings is at the deepest depths closest to the pump. These results do not show any borided tubing as EMI scanning has been deemed to not be accurate for borided tubing as the boride layer can affect the electrical and magnetic properties of the steel and give inaccurate results when EMI scanned.



Example of Tubing EMI Scan results

Shorter yellow bars indicate less pitting and wear with little wall loss

Longer red bars indicate more pitting and wear with greater wall loss

Top of graph is yellow band tubes near surface while bottom of graph is red band tubing next to pump at bottom of well

The majority of tubing failures occur near the bottom of the well due to "rod wear accelerated corrosion". Sucker rods are brushing against the tubing wall, but with minimal side loading and higher temperatures accelerate this wear-corrosion-wear mechanism of material loss. But these effects coupled with high temperature and a highly corrosive environment create a corrosion channeling effect. This brushing effect allows the passivating films to be removed which then allows for the corrosion process to accelerate in the channel where the rods contact the tubing. This effect also prevents corrosion inhibitors from maintaining a good film to protect against corrosion.

Bakken oil wells can have temperatures near the pump that will typically range between 225F to 280F. Rod buckling may also be more severe at the bottom of the well and this creates more severe sucker rod wear-corrosion-wear on tubing at these locations. In addition, the pull rods of the pumps are not guided and can wear on the very bottom joint of tubing as it strokes in and out of the pump barrel.

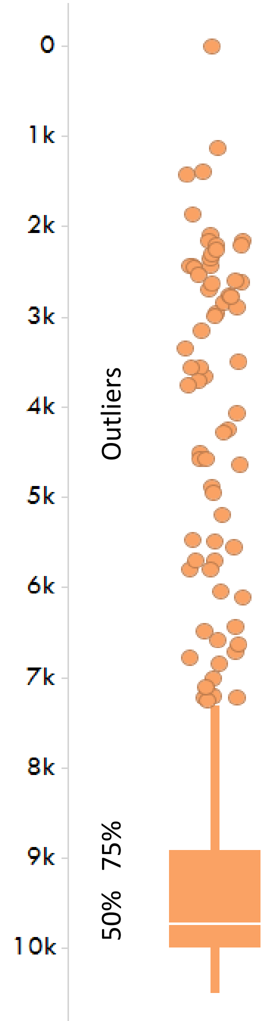
Several operators have started analyzing what locations in their tubing strings are experiencing the most hole in tubing failures and a few of these operators are now installing larger amounts of BOR-1Cr borided tubing above their pumps as they observe that the borided tubing is surviving well, but the untreated joints above their borided joints continue to fail too rapidly.

The data displayed below shows the location where hole in tubing short term failures have occurred for one major Bakken oil producer in 405 wells dating back to 2012.

It can be observed that 50% of all hole in tubing failures have occurred within 500 feet (roughly 15 joints) up from the pump

It can be observed that 75% of all hole in tubing failures have occurred within 1000 feet of the pump location (roughly 30 joints)

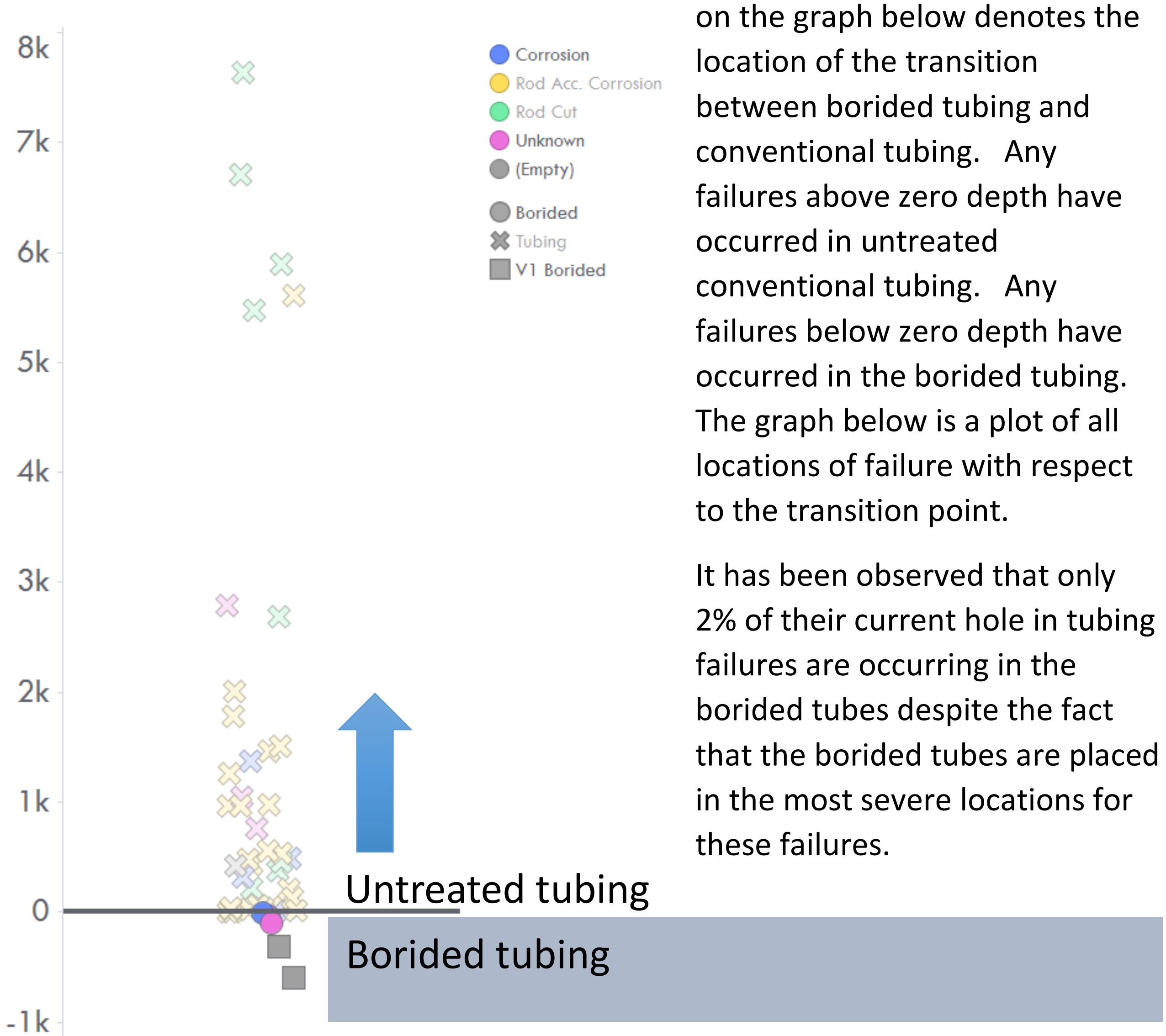
This particular operator has recently decided to increase their usage of borided joints from 2 joints per well up to twenty or more borided joints on some wells depending on history of failures in each well in order to effect a large gain in tubing string life. This longer length of borided tubing should provide additional protection to those areas that have the majority of hole in tubing failures or more frequent failures.



Count	405 tubing failures
Outliers	69
P10	4,567 ft from surface
Q1	8,915 ft from surface
Median	9,725 ft from surface
Q3	10,000 ft from surface
P90	10,156 ft from surface

The outliers at shallower depths are generally associated with collar leaks or wear associated with deviation (DLS)

This same major oil producer has also started tracking what depth any hole in tubing failures have been occurring with relation to the transition between borided tubing and conventional tubing.   A review of short run tubing failures (<450 days) from 2019 to 2011 is displayed in the graph below. The depth of zero on the graph below denotes the location of the transition between borided tubing and conventional tubing.   Any failures above zero depth have occurred in untreated conventional tubing.   Any failures below zero depth have occurred in the borided tubing. The graph below is a plot of all locations of failure with respect to the transition point.



It has been observed that only 2% of their current hole in tubing failures are occurring in the borided tubes despite the fact that the borided tubes are placed in the most severe locations for these failures.

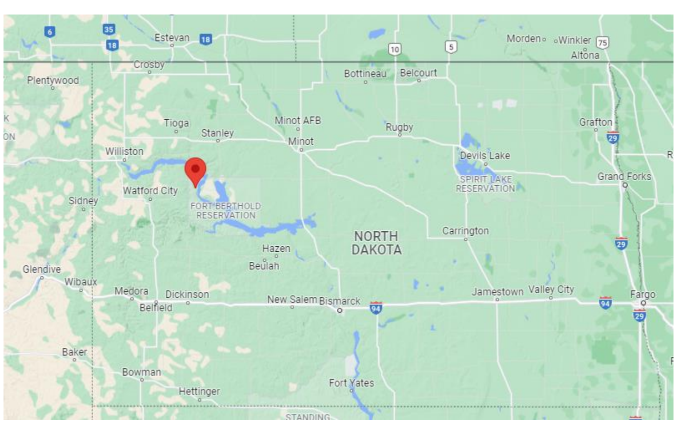
This is additional evidence that borided tubing definitely does mitigate hole in tubing failures from occurring. One can observe that the majority of hole in tubing failures are continuing to occur at the deepest depths in the regular L80 tubing sitting just above the borided tubing.   This is the reason that several oil producers have recently decided to place additional borided joints in each well to extend their wear and corrosion protection across more footage where these failures continue to persist.

<u>Experimental Design for Case Study:</u>

In the above discussion, borided tubing has demonstrated itself to be effective at mitigating hole in tubing failures. However, a direct comparison of borided tubing to untreated conventional steel tubing for wall loss that was operating in the same well under nearly the same conditions is the goal of this case study.

This will be a simple head to head comparison of borided joints to conventional L80 joints both operating in the same well next to one another in a head to head trial. Twenty (20) joints of borided BOR-1Cr tubing were installed at the bottom of this well on 4/17/21. Above the 20 borided BOR-1Cr joints, a single six foot long marker pup joint was placed such that the operator can easily identify and locate the transition from borided tubing to conventional tubing. 120 joints of new conventional untreated 1Cr L80 tubing were installed above the borided section of the well. Above the 120 new joints of 1Cr L80 in order from bottom to top, there were 42 joints of yellow band L80 tubing, 56 joints of blue band 1Cr L80, and 83 joints of blue band L80 tubing at the surface that were all being re-run.

This well was brought into operation on 4/17/21 and ran until it failed due to a hole in tubing (HIT) failure on 11/30/21 and was shut down on 12/1/21. Total days of operation with this tubing string was 229 days. This particular well is located in McKenzie County, North Dakota and is in an area of the Bakken with higher GLR's and lower water cut.



The history of this well is characterized as follows

Drilled Late 2017 in the McKenzie Bakken Field
ESP from Dec 2018- Sept 2020
Rod Lift Conversion Sept 2020- Current
Failure History-

- ESP Electrical Failure Feb 2019
- ESP Seal Failure April 2019
- ESP Electrical Failure Sept 2019
- ESP Tubing Collar Leak Failure Nov 2019
- ESP Electrical Failure Aug 2020
- Rod Lift Tubing Failure Feb 2021
- Rod Lift Tubing Failure Dec 2021

In order to characterize the corrosive agents in this well, the water and gas chemical compositions of this well are documented in the figure below.

Water Chemistry

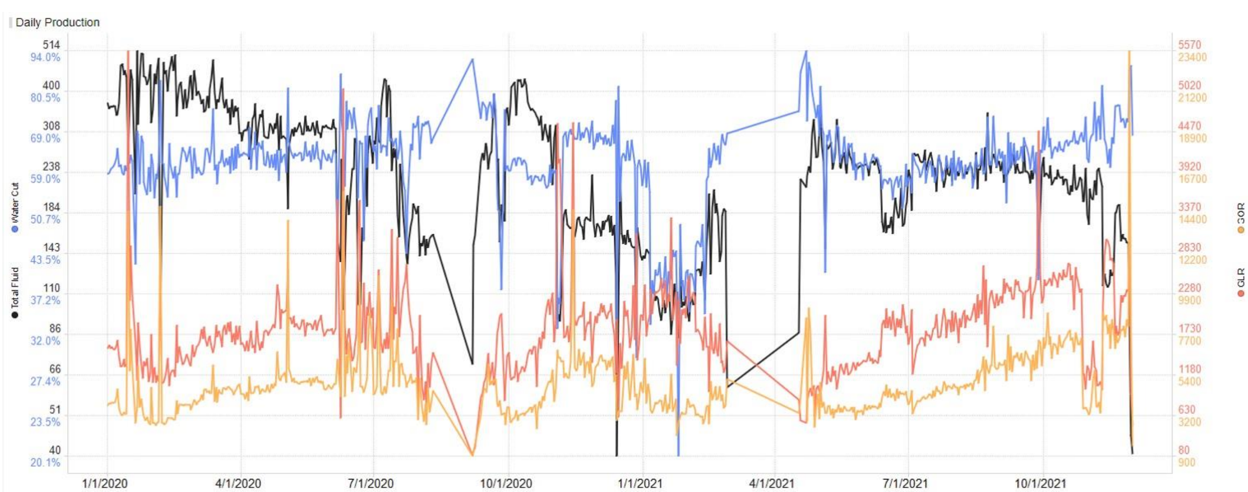
DSAT Analysis

Column	Avg
Calculated TDS	281830.37
CHLORIDE MG-L	171600.00
SODIUM	80416.69
CALCIUM MG-L	18750.00
POTASSIUM MG-L	7915.00
STRONTIUM MG-L	1243.00
MAGNESIUM MG-L	1219.00
DISSOLVED CARBON DIOXIDE	840.00
BICARBONATE MG-L	439.20
SULFATE MG-L	125.00
IRON MG-L	118.30
LITHIUM MG-L	58.22
BARIUM MG-L	23.92
ZINC MG-L	22.54
MANGANESE MG-L	9.30

Gas Chromatograph

COMPONENTFORMULA	Avg(MOLEPERCENTAGE)
C_2H_6	19.4108
C_3H_8	9.5270
CH_4	60.7920
CO_2	0.0083
H_2S	0.0000
i-C_4H_{10}	1.0008
i-C_5H_{12}	0.6013
n-C_4H_{10}	3.2861
n-C_5H_{12}	0.9379
n-C_6H_{14}	0.0087
N_2	2.7539

In order to characterize the production rates, water cut, GLR, and GOR of this well, these measurements are documented below.



Experimental Results: 24-arm caliper measurements:

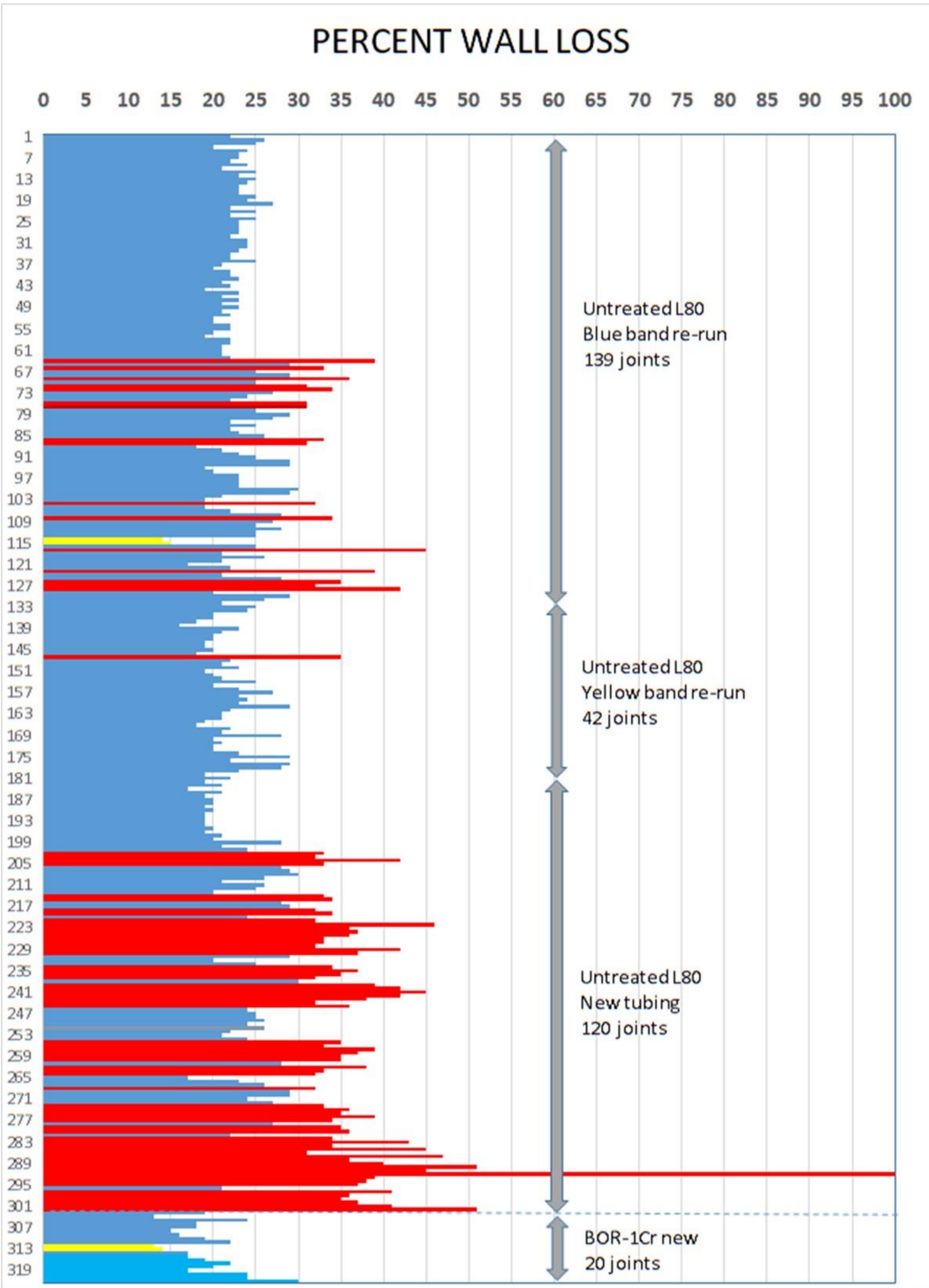
EMI scanning has not been widely accepted as a reliable method for inspecting borided tubing. It is believed that the subsurface iron-boride layer comprised of FeB and Fe_2B compounds that are typically .005" to .015" deep into the steel alters the electrical and magnetic properties of the tubing surface enough to where EMI does not work well. A mechanical method of using a 24-arm caliper tool attached to a wireline truck was selected for this study as it should be the most reliable technique for measuring borided tubing wall thickness. All of the results for comparison of borided to untreated tubing will be the 24 arm caliper measurements. This tubing was also scanned with EMI as it was removed from the well. The results from the 24 arm caliper tool will be compared to the EMI scans in a later section of this case study.

Photos below show the 24-arm caliper tool that was used to measure the tubing. This tool was lowered by wireline to a 10,000 foot depth at the bottom of the tubing string. The temperature measured at 9.500 ft depth was 229F. The caliper arms were then extended and the tool was run upwards from the bottom of the hole at 80 feet per minute as it measured the wall thickness at 24 equidistant points around the tubing bore circumference until it reached the top joint in the well. All datapoints were recorded as the caliper traversed up the well.

24 arm caliper tool

Caliper arms in retracted state

After the caliper had completed the traverse up the well and collected all of the measurement data, the data was compiled and the wireline company issued a report for each tube in the well with the wall thickness loss that had occurred on each tube. This wall thickness loss measurement represents the thinnest wall thickness measurement taken on any point within a particular tube. The results for every tube from surface (Joint 1) to bottom of the well (Joint 323) at the pump are displayed below.



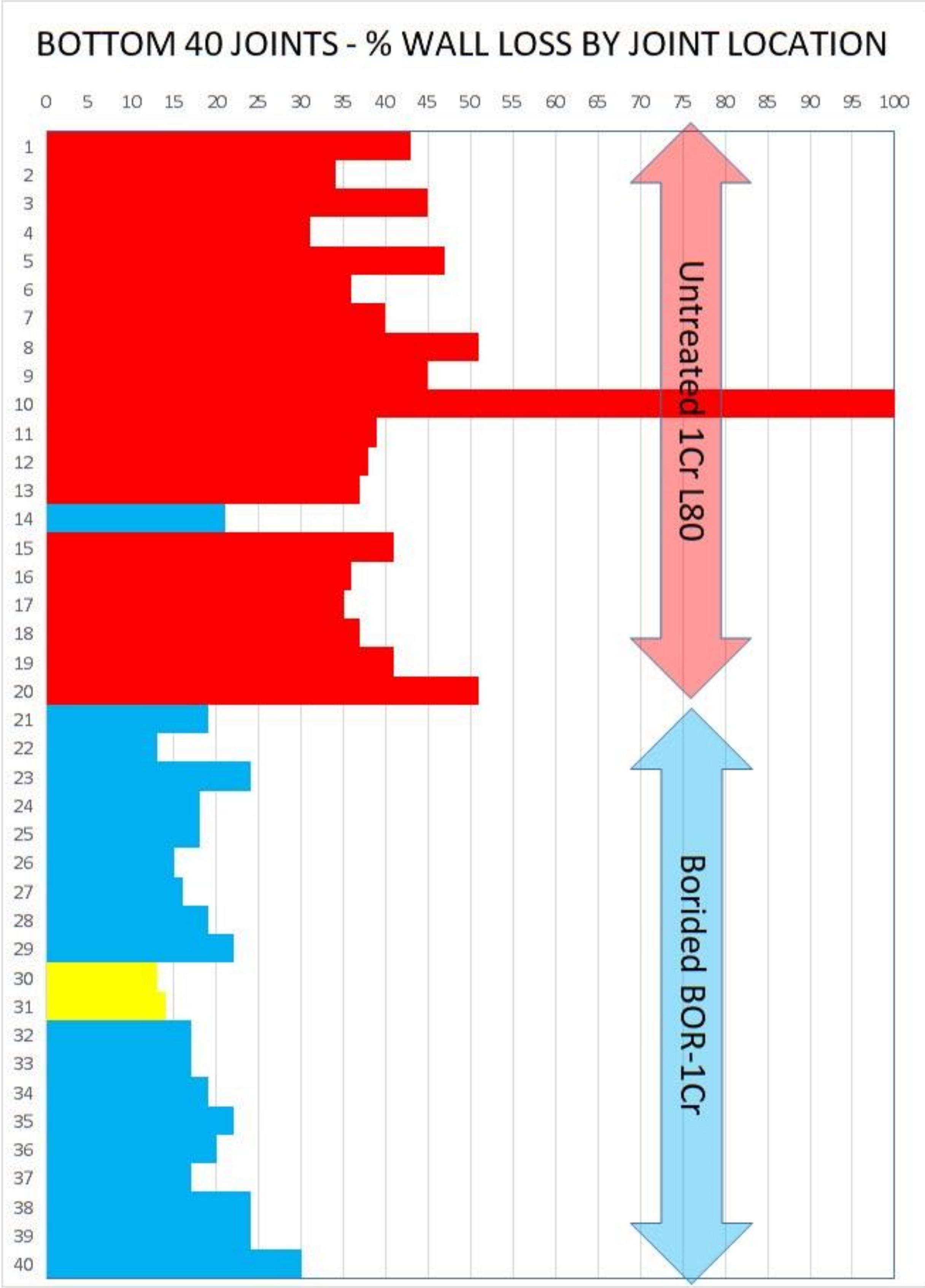
It was observed that the hole in tubing (HIT) failure had occurred in Joint #292. This was a conventional L80 tube that was sitting 10 joints above where the borided section of tubing had stopped.

All twenty of the borided BOR-1Cr tubes were measured to be either blue band (16-30% wall loss) or yellow band (0-15% wall loss). The average wall loss experienced by the entire group of twenty borided BOR-1Cr tubes was 18%.

In comparison, the next twenty untreated conventional 1Cr L80 tubes sitting above the borided section were all measured as red band (greater than 30% wall loss) except for one tube. The average wall loss experienced by the entire group of twenty untreated conventional tubes was 40%.

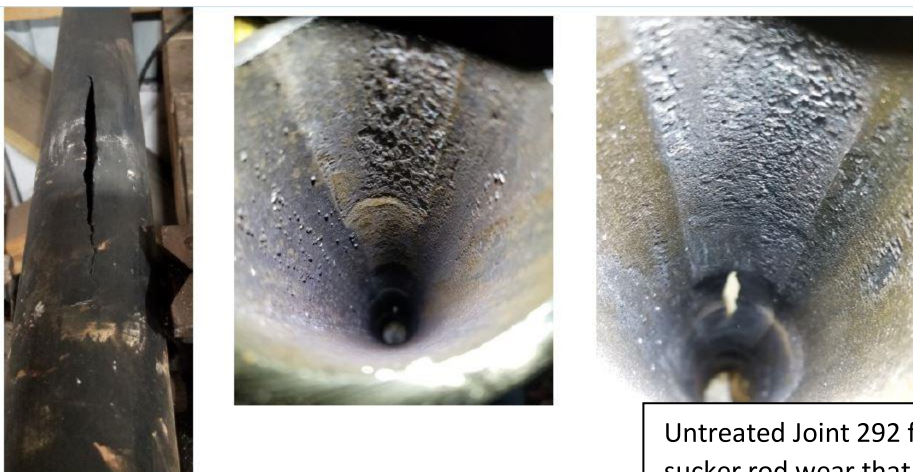
A close up display of the data for the bottom 40 tubes (20 borided BOR-1Cr, 20 conventional untreated 1Cr L80) with wall thickness loss is shown on the following page.

This is an excellent demonstration of how well borided BOR-1Cr tubing performs compared to untreated tubing. The BOR-1Cr tubing outperformed the untreated tubing where the average wall loss in the borided tubing was less than half of the wall loss observed in the untreated tubing.


BOTTOM 40 JOINTS - % WALL LOSS BY JOINT LOCATION
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40
Untreated 1Cr L80
Borided BOR-1Cr

Experimental Results: Visual Inspection of Tubing

Photographs and borescope video of both the untreated conventional tubing and the borided BOR-1Cr tubing were recorded to document the conditions of wall loss inside of the tubing. In the conventional tubing, rod wear accelerated corrosion was observed along with corrosion pitting. The joint #292 that failed had a severe wear groove from sucker rod wear that led to the wall thinning to the point where it burst open and ruptured due to internal pressure. Photographs are shown below of the conventional tubing that was worn with corrosion pitting in the wear grooves which had failed.



Untreated Joint 292 failed due to sucker rod wear that thinned the wall

Jt #292: Split Jt. UT 0.068

Untreated Joint 278 exhibiting some severe corrosion pitting

Joint 301 shows sucker rod wear. This is the bottom joint of untreated conventional L80 tubing before transitioning into the borided tubes below it

Jt #301: Wear

Jt #295: Wear / scale

Jt #258: Pitting in wear

Jt #261: Pitting in wear

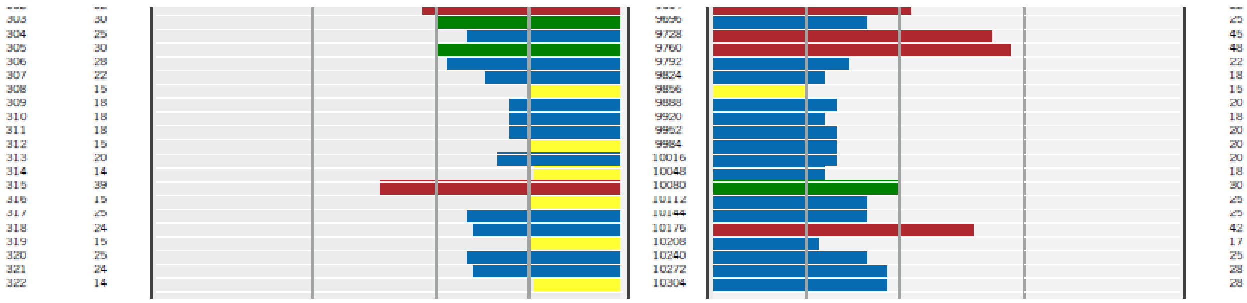
The borided tubing was also inspected with a borescope. Several joints were also sectioned and cut open to get a better look at the interior surface. The borided tubing all appeared to have only minor wear and corrosion pitting present compared to the untreated tubing. Several photographs of the borided tubing is shown below.


Borided BOR-1Cr tubing after use (Joints 320, 321, 322, 323)


Experimental Results: EMI Scanning

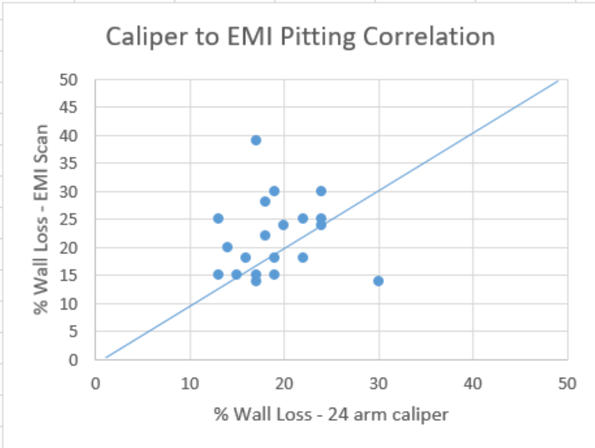
After the caliper run had been performed, the tubing was pulled from the well and each tube was EMI scanned during the pull to sort and separate yellow, blue and red band tubing.   Because EMI scanning has not been well accepted as a good measurement technique for borided tubing, we wanted to compare the EMI results to the 24 arm caliper measurements that were taken a day earlier on the same twenty borided tubes.

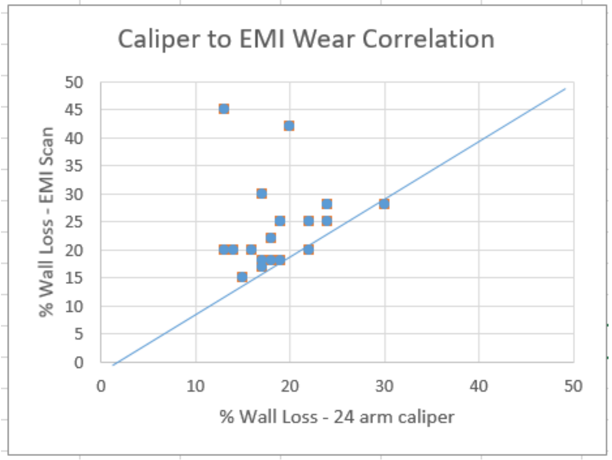
The EMI scanning results are displayed below.   The EMI scan yields two rating numbers for each tube. The bars on the left represent "Pitting" while the bars on the right represent "Wear/Split".



Correlation of 24-arm caliper measurments to EMI scan measurements

To compare the results from the 24-arm caliper measurements to these EMI measurements, the results of the 24 arm caliper measurements were plotted against the results of EMI scanning an x-y scatter plot to examine correlation of the results.   Two different charts were created since there were two numerical results from the EMI scans where each tube received both a wall loss rating for both pitting and split.   The charts for each comparison of caliper to EMI pitting and caliper to EMI split are both shown below.



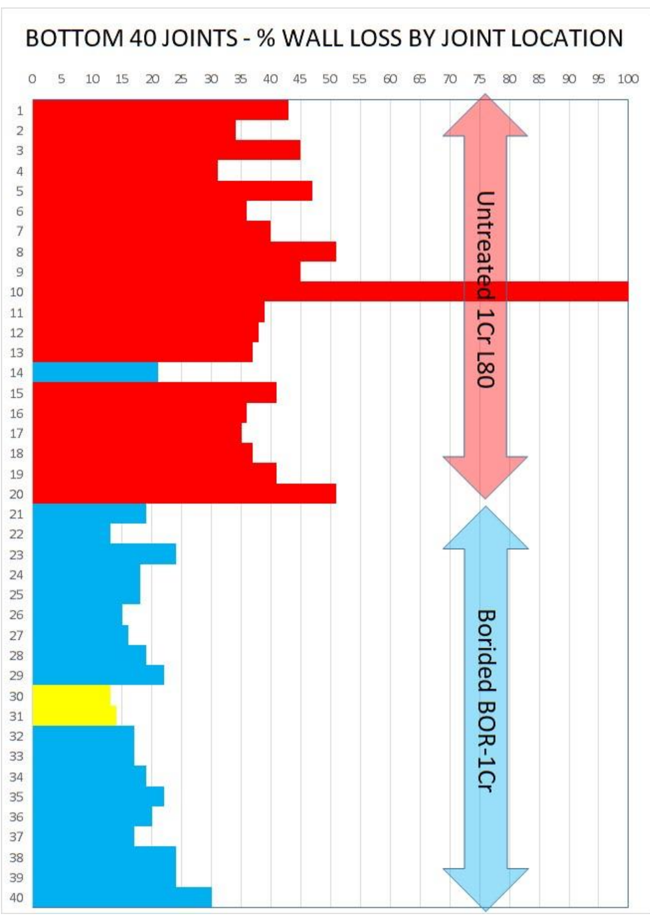


Close correlation between these two methods would produce a chart where all points lie on or close to the diagonal line where both methods would be producing identical results. Good correlation was not observed as caliper to EMI pitting data only had a correlation coefficient of 0.07 and caliper to EMI split data only had a correlation coefficient of 0.13. The results indicate that neither the EMI pitting or EMI split results correlate well to the results as measured by 24-arm caliper tool. It can be observed in the charts above that the EMI scan results were more often showing higher levels of wall loss compared to the 24-arm caliper tool. As stated earlier, the 24 arm caliper tool is likely to produce a more accurate result based on it being a mechanical measurement method that would not be affected by an iron boride subsurface layer being present in the tubing. This layer does affect the electrical and magnetic properties of the steel and is believed to affect EMI readings and produce more inaccurate results.

Four of the borided joints were also split open and visually examined in locations that indicated the worst areas of wall loss in the EMI scans. As these tubes were split open and examined visually, it did confirm that there is little actual wall loss in these locations which confirmed that the EMI scans were producing inaccurate readings as this tool is likely affected by the presence of iron-boride at the surface of the tubing.

Conclusions of Case Study:

Twenty (20) borided BOR-1Cr tubes were compared to the next twenty (20) untreated 1Cr L80 tubes located immediately above the borided tubes in a Bakken oil well after the well had failed for a hole in tubing failure. The BOR-1Cr tubes were determined to have only lost 18% average wall thickness while the untreated 1Cr L80 tubes located just above them had lost 40% average wall thickness. The hole in tubing failure had occurred 10 joints above the borided section of the well in an untreated 1Cr L80 tube. This data demonstrates that the BOR-1Cr borided tubing had less than half of the wall loss compared to regular tubing situated just above it. These results were measured using a 24 arm caliper tool. Visual inspection using a borescope video camera along with splitting joints open confirmed that only minor wear and corrosion had occurred on the borided tubing while more severe wear and corrosion pitting was present in the untreated tubing above the BOR-1Cr borided tubes.



EMI scanning was also performed on this tubing and it was determined that the EMI scanning results did not correlate well to the 24 arm caliper measurements and also the visual inspection results. EMI scanning is confirmed to not be a reliable method for inspection of borided tubing. Bluewater and our partner company who operated this well are collaborating with an EMI scanning equipment supplier to see if a new method or new equipment can be developed to accurately EMI scan borided tubing.