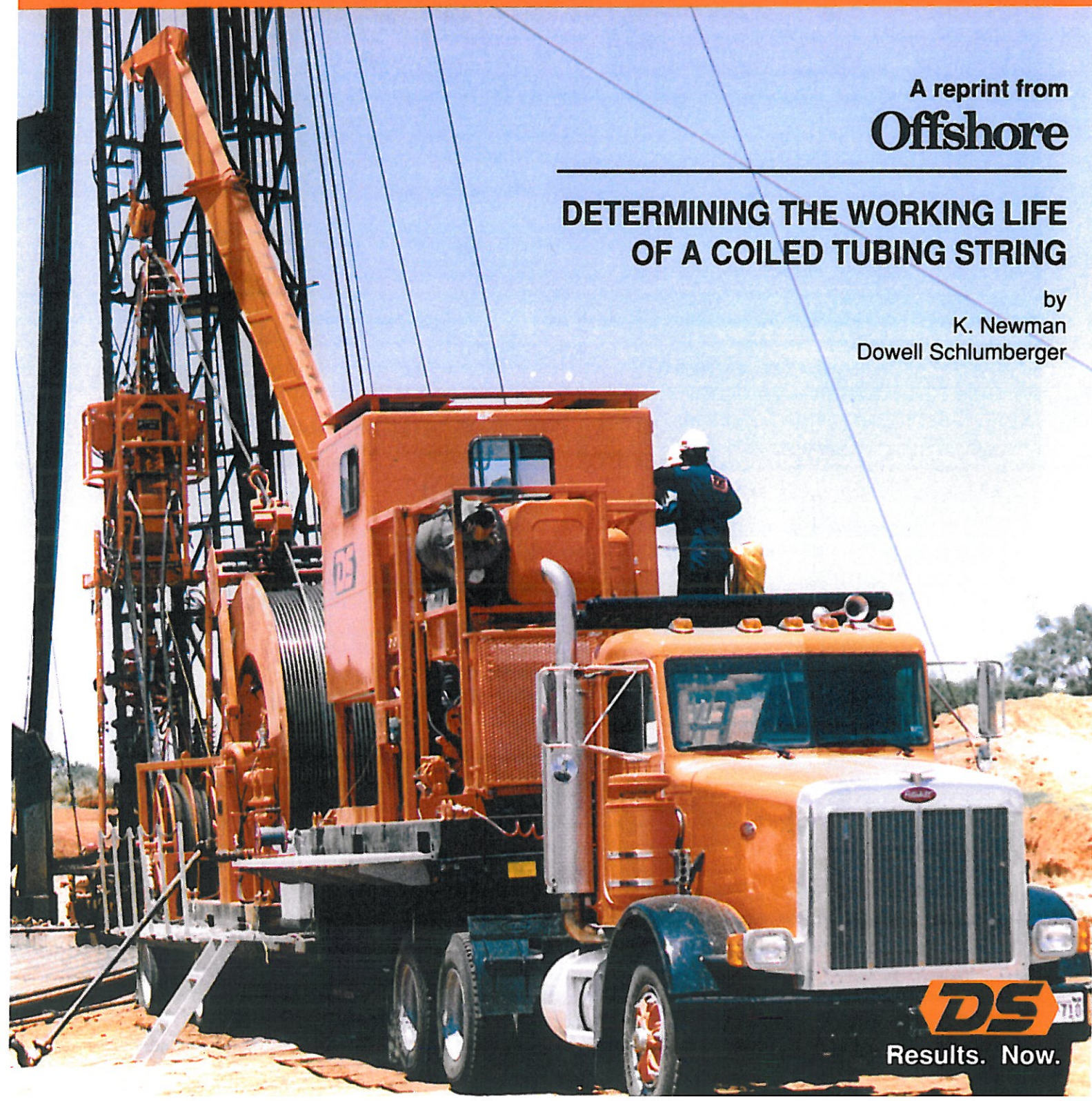**DOWELL SCHLUMBERGER**

TECHNICAL PAPER

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Offshore

DETERMINING THE WORKING LIFE OF A COILED TUBING STRING

by
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DS
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Determining the working life of a coiled tubing string

String life limited by lift, pressure, tension, diameter, and ovality.

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T he use of coiled tubing (CT) for performing completion and workover services is continuing to increase rapidly. Many of the services previously performed with snubbing, wireline, slickline, workover rigs and even drilling rigs are now being done with CT.

As the types of services being performed with CT increase, the demands on the CT pipe itself increase. It is important that the limitations of the CT pipe are thoroughly understood, before these more demanding services are performed. This article discusses the limitations of the CT pipe and the monitoring methods used to ensure that these limits are not exceeded.

Since its introduction in the mid-1960s, CT has developed a somewhat checkered history. There were too many stories about pieces or entire strings of CT left in wells. During the 1970s and early 1980s, the use of CT reached a plateau, primarily because of its poor service-quality record.

In recent years, tremendous improvements have been made in the quality of the CT pipe and in the understanding of the CT-pipe limitations. These improvements have resulted in a decrease in CT-pipe failures, and an increased acceptance of CT services.

During the first 20 years of its existence, CT was used primarily for pumping services. The pumping services still performed with CT today are:

• **Nitrogen kickoffs:** Reducing the hydrostatic pressure on the formation with nitrogen so the well can begin to slow.

• **Well cleanouts:** Cleaning out sand, fill and other debris by pumping cleanout fluids such as foam, gelled water, or oil. Cleanouts of scale, salt, paraffins, are also performed by circulating fluids such as acid and hot water.

• **Matrix acidizing:** Using CT to place and squeeze acid at the perforations to minimize acid contact with the wellbore tubulars, and to improve acid coverage of all the zones.
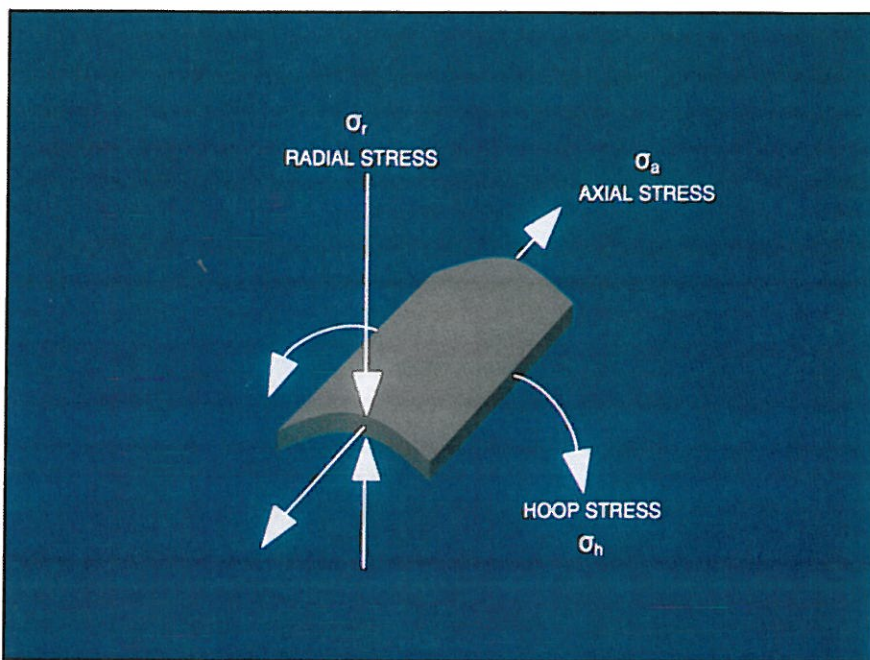

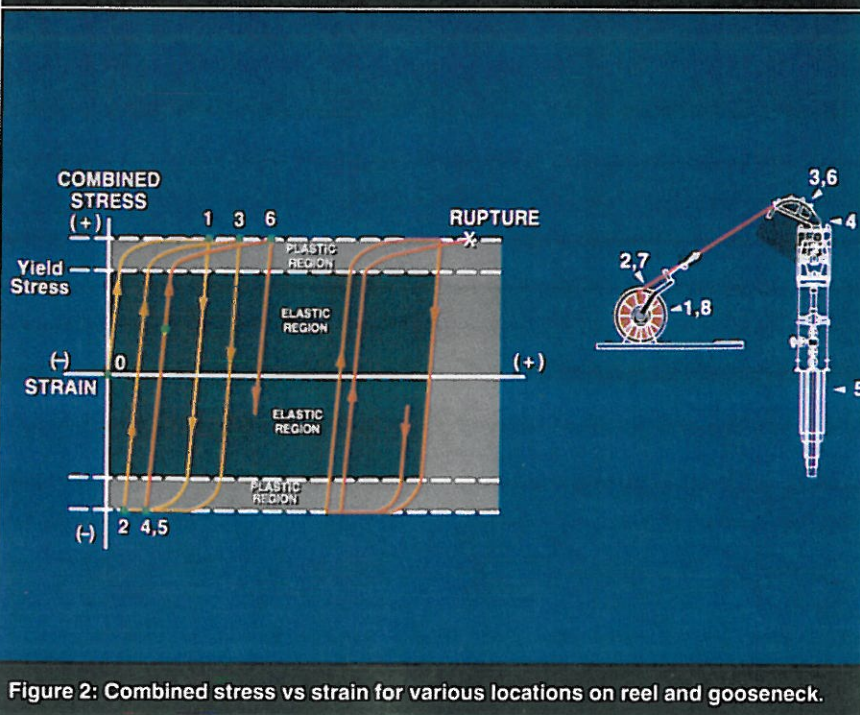Figure 1: A section of CT showing three principal stresses.

Figure 2: Combined stress vs strain for various locations on reel and gooseneck.

• **Cementing:** Using CT to place and squeeze cement into perforations or to set cement plugs.

For each of these applications, the CT pipe is only being used to convey fluids. The strength of the pipe itself is not being used to perform work. As the quality and understanding of the CT pipe has increased in recent years, more and more services are being performed which do use the strength of the pipe. There are other operations:

• **Stiffline operations:** CT is used to perform typical slickline and braided-cable operations such as fishing, pulling and setting plugs, opening and closing sliding sleeves. Because of its rigidity, CT is necessary for these operations in highly deviated wells CT is also being used for these applications in vertical wells because of its ability to wash down through fill to the plug, fish, etc. and to use both hydraulic power and mechanical push/pull at the same time, such as using a downhole, hydraulically powered, impact hammer for a fishing operation.

• **CT logging (CTL):** CT with a wireline cable inside is used to push logging tools into highly deviated wells. Although CT has been used in some cases, drillpipe-conveyed loging is usually used for open-hole logging because of the size and weight of the logging tools. CTL service is usually used in cased hole for services such as production loging and perforating. Sometimes CTL services are used in vertical wells to perform combined pumping and logging operations.

• **CT drilling:** CT is often used to convey hydraulically operated downhole motors and impact hammers for drilling out scale or cement in cased holes. Recently, CT has been used to drill open holes in place of using a drilling rig.

These types of services use the strength of the CT pipe to perform work and increase the demands on the pipe itself. To meet these demands, larger sizes of CT are being developed. Currently, pipe sizes up to 2 3/8 in. are available from the CT-pipe vendors. These increased demands and increased pipe sizes require a thorough understanding of the pipe limitations to avoid pipe failures.

Basic limits

There are three CT-pipe limitations which must be understood:

(1) Lift limits: The CT-pipe has a limited life, primarily due to the bending that occurs to the pipe when being run on and off the reel and over the gooseneck (often with internal pressure in the pipe).

(2) Pressure and tension limits: The burst and collapse pressures and the maximum tension and compression at various pressures.

(3) Diameter and ovality limits: Real-time monitoring of the pipe is required to insure that the pipe isn't ballooned, ovaled, or mechanically damaged.

Each of these limits are discussed in detail below. It is important to understand that these limits must all be considered together. For example, the life limits allow 1.25-in. OD CT with a 0.087-in. wall thickness, made of 70,000-psi yield material, with 5,000-psi internal pressure, to be cycled in and out of the hole about 40 times before reaching the limit.

This means that the pipe will not fail due to fatigue before this point. However, when the pipe reaches this limit, it will have grown from 1.25-in. OD to 1.5-in. OD. This is far beyond the acceptable diameter limit. Thus, all of the limits must be considered at the same time.

Note that the helical buckling limit is not listed above. Although it is often discussed in the industry as being a limit, helical buckling is not a limit at all. CT can be pushed into a highly deviated hole with a compressive force which exceeds the helical buckling load with no adverse affect on the CT.

The distance the CT can be pushed into a highly deviated hole is limited by helical lockup. Once the CT helically locks, the downhole end of the CT cannot be pushed further into the hole. Helical lockup does no damage to the CT pipe, so it should not be considered as a pipe limit itself. The extra stesses due to putting the CT into a helix are considered in the pressure and tension limits.
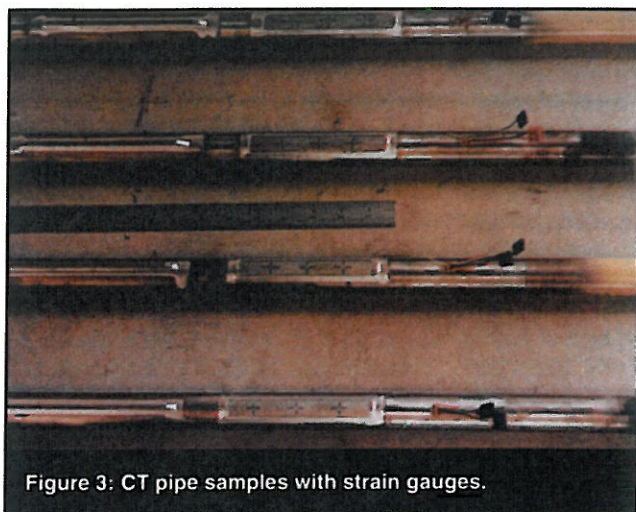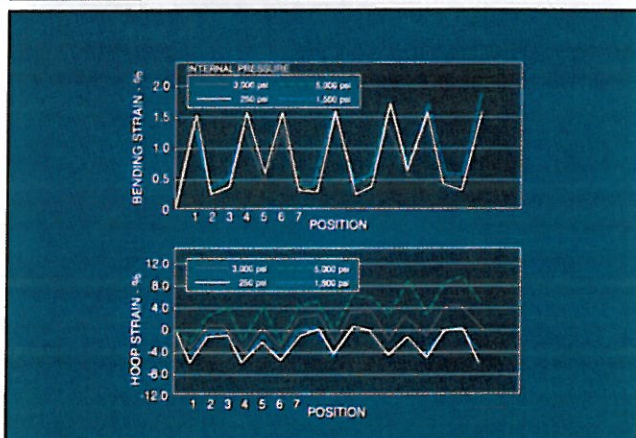

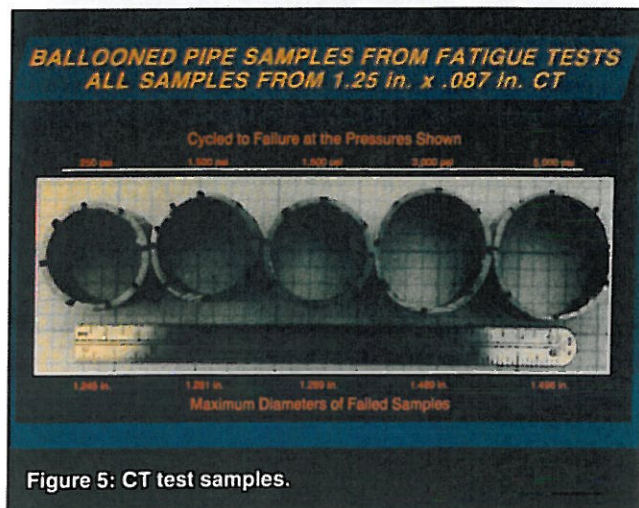Figure 3: CT pipe samples with strain gauges.

Figure 4: Strain waveforms.

BALLOONED PIPE SAMPLES FROM FATIGUE TESTS ALL SAMPLES FROM 1.25 in. x .087 in. CT

Cycled to Failure at the Pressures Shown

Maximum Diameters of Failed Samples

Figure 5: CT test samples.

Life limits

The life of the coiled tubing is limited by fatigue of the pipe as it is bent on the reel and over the gooseneck, and by corrosion. The major damage is usually caused by fatigue of the pipe.

Fatigue is an unusual material characteristic that is impossible to measure. Helicopter blades and airplane wing supports will eventually fail due to high cycle fatigue. Obviously, these failures wouldn't promote the service quality image of the aircraft industry. Even in these cases, fatigue cannot be measured. The amount of fatigue is determined by tracking the operating hours. At some point, these blades and supports are replaced.

A section of CT that has been fatigued to the end of its life can be tested by pulling it apart in a pull-test machine. It will usually pass as new pipe. The only way to avoid a CT-pipe failure due to fatigue damage is to track the fatigue damage occurring to the pipe and replace the pipe before it reaches the end of its life. Unfortunately for CT, this is much more difficult than simply measuring operating hours.

The first attempts at monitoring the fatigue life were to track the CT running feet. Running feet was defined as the total number of downward running feet the reel of CT pipe had experienced. Unfortunately, running feet has proven to be a poor way of measuring CT fatigue because it does not consider which portion of the CT has experienced the most damage. Nor does it consider the amount of pressure inside the CT while those feet were being run. Corrigan and Gray give a clear example which shows why running feet is a poor measurement of fatigue.

The second attempt at monitoring fatigue life involved counting the fatigue pressure cycles for each section (50-500-ft intervals) of the CT reel. These pressure cycle counts were then used, in empirical equations derived from fatigue testing, to determine the fatigue life. This method is obviously far superior to the running feet method and has proved fairly successful when the empirical equations used are conservative. However, there are several shortcomings to this method:
• The empirical equations are based on fatigue test in which the CT is cycled to failure on particular CT equipment at a constant internal pressure. In reality, almost every cycle of the CT is at a different internal pressure. Thus, the equations are based on tests that are unrealistic.
• Since the equations are empirical and are based on specific equipment, they do not translate to other equipment with different gooseneck and reel radii or different CT diameters, material characteristics, and wall thicknesses. Running fatigue tests for all possible combinations becomes very expensive.
• Due to the expense of many fatigue tests for many combinations of wall thickness, material characteristics, and radii, attempts were made to interpolate or extrapolate test data to cover other cases. It was soon realized that the fatigue-damage characteristics were highly non-linear and that interpolation and extrapolation were often dangerously wrong.
• The pressure-cycle counting method keeps track of the number of cycles at different pressure levels. It does not keep track of the sequence of these cycles. It was soon learned that a high-pressure cycle followed by a low-pressure cycle offered different results than a low-pressure cycle followed by a high-pressure cycle, in terms of the fatigue damage done to the pipe.

To overcome these shortcomings, Dowell Schlumberger launched a large research effort to develop a method of modelling the fatigue of the CT-pipe. The result is the ColLIFE model, which calculates the damage that occurs to the pipe for each pressure cycle, in the sequence in which the pressure cycles occur.

From this damage calculation, it then determines when the first cracking will occur. This cracking is assumed to be the end of the life of the pipe, even though the crack has not yet propagated through the wall of the pipe. Additionally, a safety factor is used, so that the pipe is actually taken out of service before this cracking occurs.
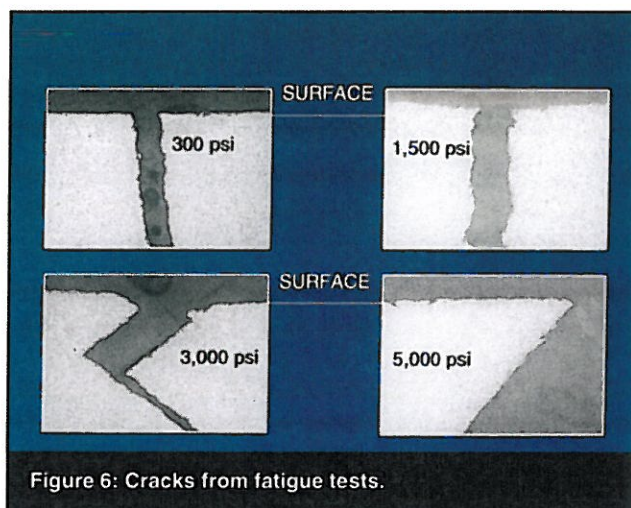
The fatigue testing done to develop
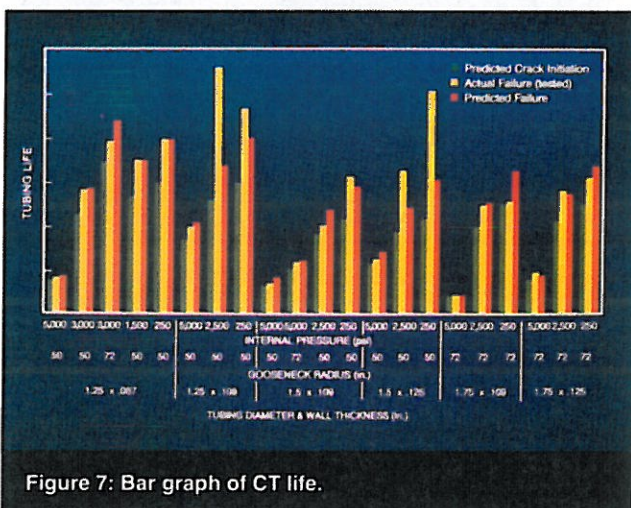

Figure 6: Cracks from fatigue tests.
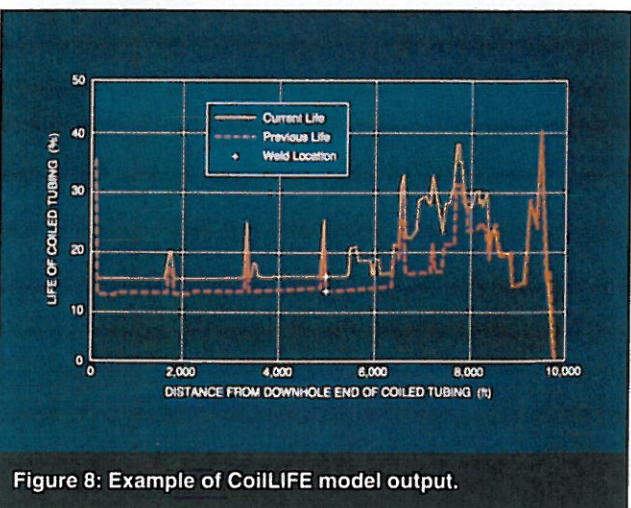

Figure 7: Bar graph of CT life.

Figure 8: Example of CoilLIFE model output.

the CoilLIFE model was quite interesting. Not only were the cycles to failure counted as in previous fatigue testing, but strain measurements also were made, both in the hoop and the axial directions (Figure 1). Figure 2 is a schematic showing the combined stresses as they are associated with the CT reel and gooseneck. This schematic shows the combined strain increasing with cycles. This only happens when the pipe is ballooning. When the pipe isn't ballooning, the curves lie on top of each other.

To measure these strains, gauges were mounted on the CT pipe at the manufacturers before the pipe was ever bent. The gauge furthest to the right in Figure 3 is simply a conventional strain gauge that measures strain in both the axial and hoop directions. It was found that conventional strain gauges could not withstand the large repeated strains to which the CT was being exposed. The left two gauges are photo-plastic strain gauges. The gauges furthest to the left measures axial strain. The gauge in the center measures hoop strain. To use these gauges, a polarized light is passed through the gauge, and viewed by a polarized filter. When viewed in this way, a rainbow pattern can be seen. The location of the interface fringes in this rainbow pattern are proportional to the strain. These gauges could withstand the large repeated strains in the CT, and thus provide the measurements required. These sections of CT with gauges on them were then cycled using a CT unit. The resulting measured-strain waveforms are shown in figure 4 for fatigue tests done to the same pipe with various internal pressures. For this plot, for the high-pressure cases, the hoop strain increases, showing the ballooning of the CT samples of the CT from fatigue tests at various pressures. For the high pressure cases, the CT grew from 1.25 in. to 1.5 in. during the testing.

The cycle testing of each CT section continued until the CT failed. Failure was defined as the point at which the pressurized water inside the CT began to leak. For low-pressure cases, the failure would be a pin hole in the CT. For the high-pressure cases, the failure would often be a more dramatic cracking of the CT. Figure 6 shows microscopic pictures of the cracks which occurred in the failed section. Note that for the low-pressure cases the cracking is perpendicular to the surface, which indicates a crack due to fatigue.

For the high-pressure cases, the cracks are at 45° to the surface, indicating

a shear-type failure. This means that, at high pressures, the damage mechanism is more complicated than just fatigue damage. At these pressures, the material is literally being torn apart by the combination of pressure bending.

It was surprising to find that in this testing, the cracks were initiating on the inside surface of the CT. Recently, CT that had reached the end of its life in the field, according to the CoilLIFE model discussed below, was brought to the engineering center for testing to determine if it was indeed near the end of its life.

The cracks that occurred in this used CT initiated on the outside surface. This discrepancy is probably due to atmospheric corrosion and mechanical damage done by the chains of the injector head on the used CT. The tests of the used CT validated the CoilLIFE model predictions.

The strain data and the laboratory data for the basic material properties relative to fatigue and corrosion were combined and the CoilLIFE analytical fatigue model was developed. Figure 7 shows a comparison of the model predictions for the point at which the first cracks will begin (green bars) to the actual test data for the point of failure from the fatigue tests (yellow bars). The red bars are the model prediction for when the actual point of failure will occur. The version of the CoilLIFE model available to the field will only be able to calculate the point

of crack initiation, since we consider this to be the end of the useful life of the pipe. Note that for the high-pressure cases, the model is quite accurate, though always conservative. In the low-pressure cases there is much more scatter in the actual test data. The model always gives a conservative prediction for these cases.
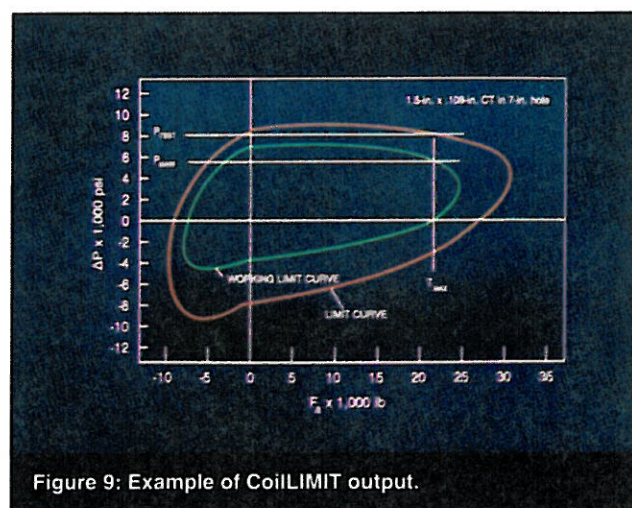

Figure 9: Example of CoilLIMIT output.

- Measures Diameter on Five Axes Around the CT
- 400 Diameter Measurements per Second
- 0.001-in. Accuracy in Each Diameter Measurement
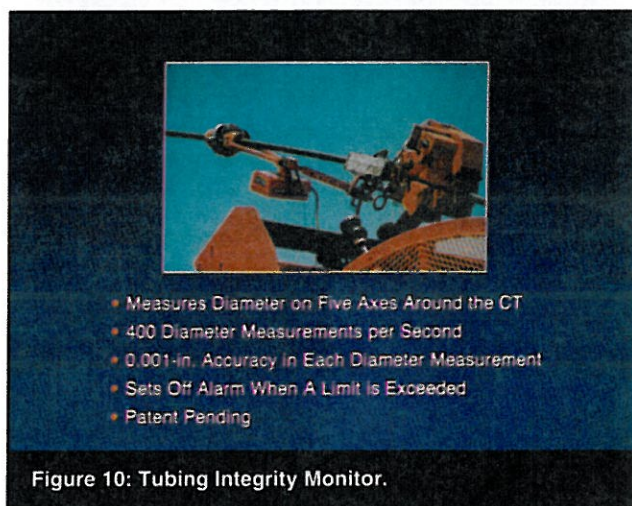- Sets Off Alarm When A Limit is Exceeded
- Patent Pending

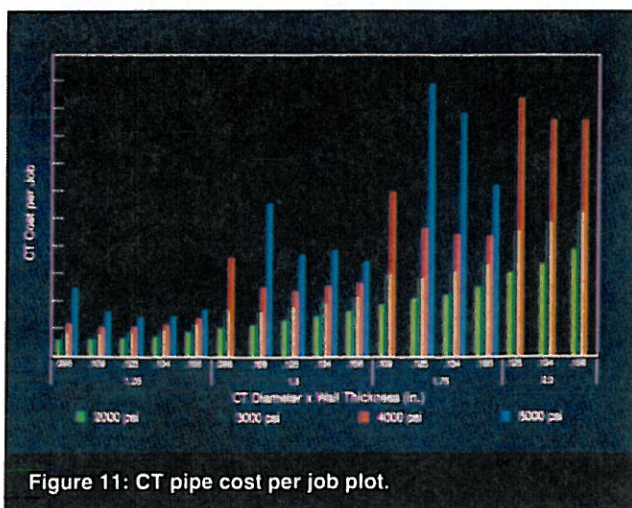Figure 10: Tubing Integrity Monitor.

Figure 11: CT pipe cost per job plot.

It is interesting to compare the predicted crack initiations (green bars) in figure 7:

• For 1.25-in. by .087-in. pipe, the pipe life increases by nearly 300% when the pressure is decreased from 5,000-psi to 3,000-psi.
• Increasing the gooseneck radius from 50-in. to 72-in. for 1.25-in. by .087-in. pipe at 3,000-psi, increases the pipe life by 54%.
• Increasing the wall thickness from 0.087-in. to 0.109-in. for the 5,000-psi, 1.25-in. case increases the life by 127%.
• Decreasing the pipe diameter from 1.5-in. to 1.25-in. for the 5,000-psi case increased the pipe life by 171%.

A computerized database is used to track the pressure-cycle history of the CT for input into the CoilLIFE model. Obviously the field engineer needs a simple presentation of the results of the fatigue analysis. Figure 8 shows an example output of the CoilLIFE model. With this type of output, the field engineer can easily see the current life condition of his CT-pipe.

Pressure, tension limits

In the past, typical pressure limits have been 5,000-psi for burst and 1,500-psi for collapse. These limits usually were adequate for various CT sizes and wall thicknesses because they tended to be conservative. Tension limits were typically set at 80% of the CT pipe vendor's published yield limit. In most cases there were no compression limits considered, as CT was usually in tension. With the advent of larger pipe sizes and horizontal wells where the CT is in comprssion, these limits need to be re-examined.

Figure 9 shows an example output from the CoilLIMIT model. The X axis is the axial force on the CT pipe (positive for tension and negative for compression). The Y axis is the differential pressure on the pipe (inside pressure minus outside pressure). A positive differential pressure is burst pressure, and a negative differential pressure is collapse pressure. The limit curve shown is the conservative limit based on the Von Mises yield criterion. The wall thickness of the CT is reduced to account for acid corrosion which reduces the limit curve.

Note that the left side of the curve is truncated when compared to the right side. This is due to the fact that the CT pipe goes into a helix when a compressive force is applied. The additional axial stress in the pipe due to this helix causes a reduction in the compressive load that can be applied before yielding occurs.

The inner curve, called the working-limit curve, is the outer curve with a safety factor applied. Note that the lower portion of the curve has a larger safety factor to account for the ovality of the CT in determining the collapse pressure.

The CT-unit operator in the field needs to have a simple way of understanding these curves. For the upper right quadrant, the curves can be simplified by defining a maximum allowable working pressure (Pmaw) and a maximum tension (Tmax) as shown. Following the rules used today for wellhead equipment, the test pressure (Ptest) is 150% of Pmaw. These two limits apply as long as the CT in is tension, and the differential pressure is positive. This handles the majority of vertical CT jobs. For the other cases, a working limit curve must be generated.

Diameter, ovality limits

During the course of its life, the CT pipe may balloon, neck down, and/or become ovaled. Also, mechanical damage (that can't be predicted by a computer model) often occurs to the CT. No computer can predict that someone will back a forklift into the reel or that a stone will put a dent in the reel during transit or any of the other things that happen every day. Often this mechanical damage is not easily seen.

To find these types of problems, real-time monitoring of the CT is required. A T.I.M. Tubing Integrity Monitor that does this type of monitoring has been approved by Det norske Veritas for use in a zone II area (Figure 10). The T.I.M. monitor makes 400 diameter measurements per second with 0.001-in. accuracy, on five axes around the pipe. The diameters are transmitted to a display in the CT-unit control cab which displays the maximum, minimum and average diameters graphically. The distance between the maximum and minimum diameter lines indicates the ovality. The display sets off an alarm when the diameter or ovality limits are exceeded.

Field experience has already proven that the T.I.M. monitor often locates pipe problems never noticed otherwise. The number of cases where pipe is ballooned, necked or ovaled beyond the limits are relatively few, when the CoilLIFE and ColLIMIT limits are followed. Several cases of previously unknown mechanical damage have been found.

Cost implications

Figure 11 combines the limits to show the cost of the CT pipe per job. This plot considers both the fatigue life and the diametral growth of the pipe, to calculate the cost per job for a job that occurs at a constant pressure. Note also that some of the 5,000-psi bars are missing. In these cases, the 5,000-psi bar would be a long way off the scale of the graph.

It is clear from this graph that using large diameter CT at elevated pressures becomes very expensive when compared to smaller diameter pipe. The graph also shows that heavier wall pipe, although it is more expensive to buy, can be less expensive overall because of the increase in pipe life. ◘

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