INTEGRA®
TECHNOLOGIES

ECHO™ PRECISION BOLT LOAD MONITOR

HOW IT WORKS

PRECISION
BOLT LOAD MONITOR

Bolting The World's Critical Joints

1-800-779-2658 **www.integratechnologies.com**

OVERVIEW

INTEGRA introduced the use of ECHO™ services to the international petro-chemical and power generation markets and is the world's largest supplier of this precision service.

The only way you can be absolutely sure about changing pressure in a bolted assembly is to measure bolt stretch and the only practical way you can do that is with ultrasonic testing. Everything else is guesswork, and guesswork can be dangerous, costly and result in shutdowns.

When conventional wrenches or bolt heating torque wrenches are used, it is virtually impossible to be sure of the precise stress placed on the bolts. Bolt loadings are often uneven and above or below proper specifications.

Ultrasonic testing instantly provides a digitized readout on bolt loading, providing the means for the operator to adjust the loading to meet design specified clamping pressure.

ABOUT THE TESTING UNIT

The unit is highly portable and simple to operate. These portable versatile units are used by specialty certified INTEGRA technicians. Ultrasonic read-outs are displayed on a digitized oscilloscope providing information on bolt load, stress or elongation characteristics. The unit is self-calibrating and has the capability of uploading and downloading data for reports and analysis.

BENEFITS

- Proper Sealing
- Improved Safety
- Prolonged Service
- Verified Documentation

HOW IT WORKS

This description starts with a brief review of the history of ultrasonic measurement of bolt and stud preload. Next, the basic principles of operation are covered, followed by a discussion of how ultrasonic measurement is used with conventional bolting tools and procedures. After this, the advantages and disadvantages of ultrasonic control of preload are discussed. These advantages and disadvantages are used, in part, to illustrate some of the things – such as long-term relaxation and load or temperature effects on preload – we've never been able to monitor before, except by strain-gauged sampling of a few fasteners. The paper concludes with a discussion of a number of case histories that illustrate that use of ultrasonics on equipment such as heat exchangers, reactor vessels, and hydrocrackers. These field results show the pattern and scatter in preload achieved by conventional tools and procedures and how scatter can be reduced by ultrasonic measurements. Although the experience to date is limited, it suggests that a uniform preload, to the stress levels specified by the *Boiler and Pressure Vessel Code*, is sufficient in most cases to prevent leakage.

For at least 15 years attempts have been made to use ultrasonics to measure bolt preload the, the tension in a tightened bolt or stud. For example, conventional time-of-flight thickness gauges were used in an attempt to detect the small change in length that occurs when a fastener is tightened. The time required for the ultrasonic signal to make a round trip in the fastener is, however, affected by the change in stress level in the fastener (ultrasonic velocity decreases as stress increases) and by the increase in path length. A conventional thickness gauge doesn't expect to encounter a stress change, so it gives a "wrong" answer that must be analyzed to determine the actual change in the "thickness" (length) of the bolt. It is not a simple matter to predict the ratio between the stress effect on transit time and the strain effect, even today. As a result, the data obtained with conventional ultrasonics required too much analysis and interpretation to be of practical use in the field.

Another problem with conventional ultrasonics was the high resolution required to measure the tiny changes that occur in a bolt as it is loaded. Measurement accuracies of 0.0001 or even 0.00001 inch are required; at least in short fasteners, and thickness gauges in general did not have the required accuracy. More sophisticated studies, by McFaul and Martin [1], Rollins [2], Bobrenko [3], and others, involving such things as interferometric techniques and the comparison of transverse and shear wave velocities, showed more promise but also showed that ultrasonic measurement of preload was not a simple task. However, the need for accurate preload control, to fight such things as fatigue, vibration loosening, and leaks, remained to that interest in ultrasonic measurement persisted in spite of the difficulties. Since 1976, a number of instruments (some of them digital) have been placed on the market.

Although ultrasonic measurement of preload is still not widespread, the practical problems are slowly being overcome, the costs are coming down, and usage is increasing. Recent work, for example, has involved such things as bridges, critical joints in natural gas compressors, off-road construction equipment, foundation bolts in nuclear construction, and critical joints in refineries and petrochemical plants where the goal is leak prevention. Some case histories are presented below.

PRINCIPLES OF OPERATION

The principle of operation of a typical digital extensometer is fairly straightforward. A pulser within the instrument shocks a transducer which then delivers a brief, highly damped pulse of ultrasound (typically about 1 ½ cycles) to one end of the fastener. This pulse travels through the fastener, echoes off the far end, and returns to the transducer. The instrument measures the transit time, or time of flight, required for the pulse to make the round trip. The time is entered in the memory bank of the microprocessor inside the extensometer. The bolt is then tightened, increasing the length of the path the signal must travel and decreasing the velocity of the ultrasound. The new, increased transit time is also entered in the microprocessor's memory.

The microprocessor computes the total change in transit time computes and discards the portion of the change that resulted from the change in velocity, and presents readout of the actual change in the length of the fastener. Note that in order for the microprocessor to give a read-out of the actual change in length, it must make and statistically average a large number of measurements of transit time. This is because the change between unstressed and stressed transit times is very small – a fraction of a nanosecond. To interpret such as difference accurately enough with only one measurement would require logic and timing circuits operating at megahertz or gigahertz speed. This would mean state-of-the-art logic, presently available only under laboratory conditions, and that would mean a log of field problems and a very high unit cost. Since measurement errors will be randomly scattered, however, taking many measurements and computing their statistical mean can obtain a suitable degree of accuracy.

One other factor must be considered. A temperature change will affect the length of the fastener and the velocity of the ultrasonic signal. If the temperature of the fastener changes between stressed and unstressed readings, the influence of temperature on velocity and length must therefore be factored out by the microprocessor.

USING AN EXTENSOMETER

Before an extensometer can be used, it must be calibrated on a sample of the fastener who's preload is to be measured, since accurate calculation of the relationship between preload and change in transit time is not possible at the present time. The manufacturer or distributor usually performs this calibration, but it can be done in the customer's shop if necessary. Subsequent recalibration in the field – to check the instrument or to return it to the calibration required for a different job – is done by setting a pair of switches on the back of the instrument and then verifying the switch positions by reading a calibration block provided with the instrument. If it is necessary, the switches are adjusted slightly.

After calibration, the instrument is ready to use as follows:

1. The instrument is placed in the "length" mode.
2. The temperature of the bolts to be tightened is measured, and the digital temperature switch on the front panel is set.
3. A drop of acoustic couplant, such as glycerin or oil, is applied with a squeeze bottle to either end of the fastener, and the transducer is set in place.
4. The initial length of the fastener now appears on the readout. This length is recorded for future reference.
5. All other bolts in the joint, or a selected sample, are measured, and their initial lengths are recorded in the same way.
6. The instrument is now switched to the "change of length" mode.
7. Tightening each fastener – presumably in a cross or star pattern – to perhaps 20 or 30 percent of the desired tension, now pulls the joint together. The extensometer could be used to control this process, but this would be time consuming and unnecessary. A more common procedure is to use torque control for this pass. The lengths of a few fasteners are monitored with the extensometer at the end of the pass to make sure that the results are reasonable.
8. Additional passes are now made, and the bolts are tightened to a higher percentage of the desired preload. A small sample of fasteners is measured with the extensometer at the end of each pass, but torque is still used for control.
9. The extensometer is used to control the tightening process when about 70 percent of the desired preload is exceeded (depending somewhat on the one's sample results in Steps 7 and
10. The general procedure for measuring a partially or fully tightened fastener is as follows:
    a. A new drop of acoustic couplant is placed on the fastener, and the transducer is set in place.
    b. The instrument is now calibrated for the initial reference length of the fastener, as recorded in Step 4. At this point the readout on the extensometer will show the change in length between the original reference length and the present length, that is, the stretch that has been imparted to the fastener less any relaxation that has occurred since tightening.
    c. The fastener is now tightened some more; the instrument displays the cumulative stretch.

   d. If the temperature of the fastener has changed from the first to the present reading, the instrument must also be adjusted when one returns to the fastener. However, one never needs to keep a log of initial or present temperatures.

11. It is usually wise to re-measure every fastener in the joint after the final pass in order to monitor final relaxation effects. It is especially important to re-measure the fasteners that were tightened first, since these are the most likely to relax.

ADVANTAGES OF ULTRASONIC CONTROL

Ultrasonic control offers the following advantages:

1. Controlling bolt preload by ultrasonically measuring elongation is far more accurate than torque and/or turn control.
2. In an actual field situation, all the bolts in a joint can be measured and controlled in this way, not just a few strain-gauged samples.
3. Ultrasonic measurements of stretch are more accurate than measurements made with a micrometer. And if the operator is skilled, ultrasonic measurements are faster than measurements made with a micrometer. Note, too, that one needs access to only one end of a fastener to measure it ultrasonically.
4. Both dynamic and static measurements can be made, and residual preload can be measured at any time after the initial tightening. This means that one can monitor short- and long-term relaxation effects, external load effects, temperature effects, vibration loosening, fatigue loading, and the like. Again, these things can be done on all of the bolts in a joint, not just a few strain-gauged samples.
5. The extensometer can be used to control any kind of tool, from a torque wrench to a tensioner to a slug or impact wrench. For example, the fastest way to do a job is often with an impact wrench. Using the extensometer for control makes this a very accurate procedure.
6. Using an extensometer for control can often speed up a job. For example, a joint can often be put together with fewer passes, because one can see and compensate for relaxation effects, bring up all the fasteners together, avoid over-tightening, and so forth.

DISADVANTAGES OF ULTRASONIC MEASUREMENT

Given the present state-of-the-art, there are also some disadvantages to ultrasonic measurement:

1. In order to obtain the most accurate readings, the instrument must be recalibrated for each new application. The calibration procedure is simpler than it was a few years ago, but it is still necessary.
2. It takes a fair amount of operator skill to use the instrument. Such factors as selection and placement of the transducer, what to do if signal strength is seriously reduced by bending in the fastener, and a phenomenon called "peak jumping" all require a trained operator.
3. The results obtained with the extensometer are often a surprise. Jobs can be slowed or stopped as engineers struggle to analyze, explain, and compensate for some of the things revealed by the extensometer. It must be recognized that the phenomena revealed by the extensometer have always been present; it's just that they have never been observed before. Once the phenomena are observed, one must explain and/or do something about them.

4. It is necessary to keep a log of the original length of each fastener if one wants to tighten a joint in multiple passes or make long-term measurements.

MEASUREMENT ACCURACY

The instrument is capable of resolving 0.0001 or 0.00001 inch, but accuracies like these are possible only in aerospace, laboratory, or quality control conditions. In most work at construction sites or petrochemical plants, the measurements are usually accurate to the nearest 0.005 or 0.001 inch, and the measurements are used to control preload within 5-15 percent.

CASE HISTORIES

In petrochemical applications, the extensometer is usually used in an attempt to prevent leaks. Our limited experience suggests that it is capable of doing this. We have tightened 94 joints in 15 locations and have had only 4 leaks that we know of. One of these was traced to a badly damaged flange surface, a second was blamed on rust particles between the gasket and the flange surface, and the final two were apparently caused by the customer having specified a stud preload that was only a fraction of the preload permitted by the code. Virtually all of the joints we have been involved with have been considered chronic leakers.

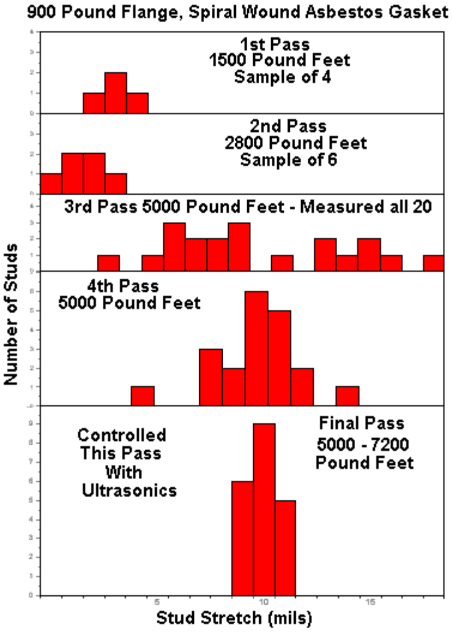
All of this should, however, be received with considerable caution at the present state-of-the-art. Extensive experimental and analytical work currently being sponsored by the Subcommittee on Bolted Flanged Connections of the Pressure Vessel Research Committee [8,9] shows that it is not easy to answer the question, “When and why does a gasketed joint leak?” There are many possible variables, many of which have not been explored in the tests performed to date (for example, uniformity of preload). It will be many years before we’ll be able to say with confidence what is required to prevent leaks. All that the results below can do is show the preload achieved in the handful of joints we’ve helped to tighten – joints that, because of these preload conditions or in spite of them, did not leak.

In general, in our bolting work we have followed the tightening procedures described above and have usually used a hydraulic wrench to do the tightening. Torque is used for control during the first few passes; we monitor a few or all fasteners with the ultrasonic equipment to make sure that everything is normal. Extensometer control is used only on the final passes. The torque required to achieve the final stretch may or may not be recorded and is immaterial except for the insight it provides on the behavior of the joint.

Figure 1 is a series of histograms that show the data taken during a typical service job. In this case, the flange was on a ball-type reactor processing unleaded gasoline. There were 20 studs, 2 ½ - 8 x 12 in size. The stud material was B16, and the grip length was 5 ¾ inches. A nickel anti-seizure compound was applied to the threads.

As shown in Figure 1, the studs were tightened in five passes. The first pass was made at 1500 pound-feet of torque, which was applied to the fasteners in a cross pattern. After all the studs had been tightened, four were selected at random and their stretch was measured for reference purposes. The stretch measured in these four passes is shown in the top histogram in Figure 1 and averaged 3.5 mils. Calculations show that this corresponds to an average stud stress of 12,727 pounds per square inch (at the root diameter of the threads).

After a second pass at 2800 pound-feet, 6 studs were checked. Note that the average stretch achieved here was only 2 mils (7273 pounds per square inch), which is less than that achieved at 1500 pound-feet. This is an apparent violation of the formulas that relate applied torque to achieved preload. What's happening, of course, is that the joint is relaxing faster than it is being tightened. In fact, it is not at all uncommon for all of the stretch (preload) produced in the studs by the first few passes to disappear completely between passes. The amount of stretch detected at the end of a given pass depends as much on the amount of time that has elapsed between tightening and measuring the stretch as it does on the applied torque. This doesn't mean that the early passes are unnecessary – they're essential to pull the joint together with minimum distortion of the gasket. However, it's not necessary to re-tighten at low torque values until a low but stable preload is achieved. This takes many passes and is a complete waste of time.



Note: Torque control was used on the first four passes; urltrasonic control was used on the last. This joint was on a ball reactor that processed unleaded gasoline.

Figure 1-- Histograms Showing the Stretch Achieved in Twenty 2½-8 x 12 B16 Studs Tightened in Five Passes

The next two passes were made at a torque of 5000 pound-feet. This time the stretch achieved was measured in each fastener, not just a sample, before proceeding to the next pass. Again, torque, not stretch was used for control.

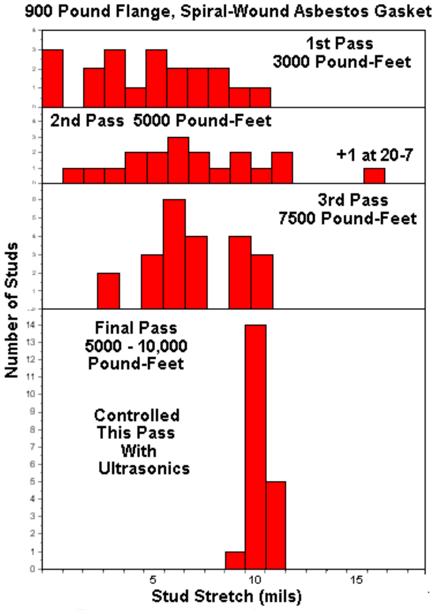
As can be seen from the third histogram in Figure 1, an average stretch of 10.45 mils (38,036 pounds per square inch) was achieved in the studs by the first pass at 5000 pound-feet. There was, however, a substantial amount of scatter in this result, with actual stretch varying from 3.3 mils (58 percent less than the average) to 18 mils (72 percent more than the average). A second pass at 5000 pound-feet increased the average slightly (to 11.7 mils, or 42,545 pounds per square inch) and reduced the scatter (from –43 percent to +34 percent of the average).

The final pass was made under extensometer control. Some relaxation occurred after the second pass at 5000 pound-feet, so the final average stretch achieved (and accepted) was 9.28 mils (33.745 pounds per square inch). The minimum stretch accepted in any stud was 8.2 mils (28,818 pounds per square inch), or 12 percent below average. The maximum accepted was 10.3 mils (37,454 pounds per square inch), or 11 percent above average. We could have done much better than this as far as scatter was concerned but it was considered unnecessary. This joint subsequently passed hydrotest, and the reactor was restarted without a leak. Note that torques ranging from 5000 to 7200 pound-feet were required to achieve the final preload.

Earlier, this is called a typical joint. It is typical for many reasons:

1. Early passes under torque control produced a very wide scatter in preload, as shown by the first pass at 5000 pound-feet. Scatter of ±50 – 75 percent is not uncommon as a joint is pulled together and relaxation effects are fought. The theoretical torque-preload scatter of ±30 percent so often mentioned in the literature is rarely achieved in large gasketed joints.
2. Subsequent torque control passes tend to reduce the scatter but to not eliminate it, as shown by the second pass at 5000 pound-feet.
3. A joint such as this relaxes so much between the early passes that it is not uncommon to achieve less average stretch with a higher torque than one has previously achieved on the same joint with a lower torque (compare the first and second passes). This shows how difficult – it might be more accurate to say impossible – it is to predict the exact amount of preload that will be achieved under pure torque control in a gasketed joint.
4. The final residual preload specified and accepted in this reactor joint corresponds to an average bolt stretch of approximately 35,000 pounds per square inch, slightly less than the 1 ½ x 25,000 pounds per square inch permitted by the *Boiler and Pressure Vessel Code* for a B16 bolt of this diameter. This is the sort of stress level that petrochemical customers commonly ask for. (The customer, not Raymond, always specifies the target stretch or stress.)
5. The final preload scatter of roughly±12 percent that was accepted in this joint is typical. This amount of scatter is much easier to achieve than the ±1-2 percent possible, and has usually been good enough to prevent leaks, as it was in this case.

Figure 2 shows a similar set of histograms, which reflect data taken as we tightened another reactor flange. This flange also involved twenty 2 ½ - 8 studs. Torque alone was used to control the first three passes at 3000, 7500, and 7500 pound-feet, but this time all of the studs, not just a sample, were read ultrasonically after each pass. The final pass, which was under ultrasonic control, required torques ranging from 5000 to 10,000 pound-feet. The histograms in Figure 2, like those in Figure 1, show typical patterns of preload scatter, relaxation, and so forth.



Note: Torque control was used on the first three passes; urltrasonic control was used on the last.

Figure 2-- Histograms Showing the Stretch Achieved in Twenty 2½-8 x 12 B16 Studs Tightened in Four Passes

Figures 3 and 4 show a different view of the results achieved when torque is used on a gasketed joint. In this case the extensometer was used only to measure the preload in the studs, not to control the process. We wanted to see why uniform torquing didn't always prevent leaks (as part of an in-house effort to define a "better" torquing procedure). The results shed light on why extensometer control is useful.

There were sixteen 1 ½ - 8 B7 studs in this 10-inch 600-pound flange, sealed with a spiral-wound asbestos-filled gasket. The studs were lubricated with moly paste and were tightened in a cross pattern. The stud numbers refer to the sequence in which the studs were tightened, with Stud 2 located 180 degrees away from Stud 1 on the flange. Studs 3 and 4 located 90 degrees from Stud 1, and so forth.

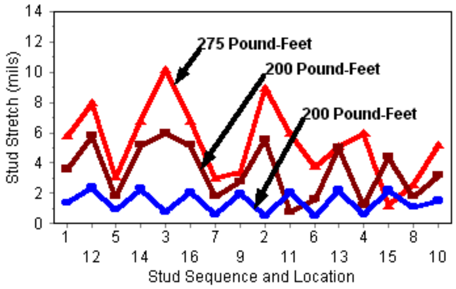
Figure 3 shows the preloads measured in each stud after the completion of each of the first three cross-pattern passes at 100, 200, and 275 pound-feet of torque. Note that a fairly regular sawtooth pattern of residual preload was found after Pass 1 – and after some relaxation had occurred. The preload initially introduced to each stud, by 100 pound-feet of torque, is not shown on the graph but was very consistent. It was relaxation, and possibly cross-talk as other fasteners were tightened, that developed the residual sawtooth pattern.

Subsequent passes at 200 and 275 pound-feet (also shown in Figure 3) modified and accentuated the sawtooth, resulting in a range that was nearly 5:1 in the final, relaxed preloads in the studs (for example, compare Studs 3 and 15).

We next tried to reduce the preload spread by making four more passes on this joint at 275 pound-feet, this time following a clock pattern instead of a cross pattern. The final preloads are plotted in Figure 4. Thanks to those four passes, the final pattern in Figure 3 was raised a bit (all the studs were tightened slightly), but there was very little change in the basic pattern. The scatter, however, was reduced from nearly 5:1 to less than 3:1.

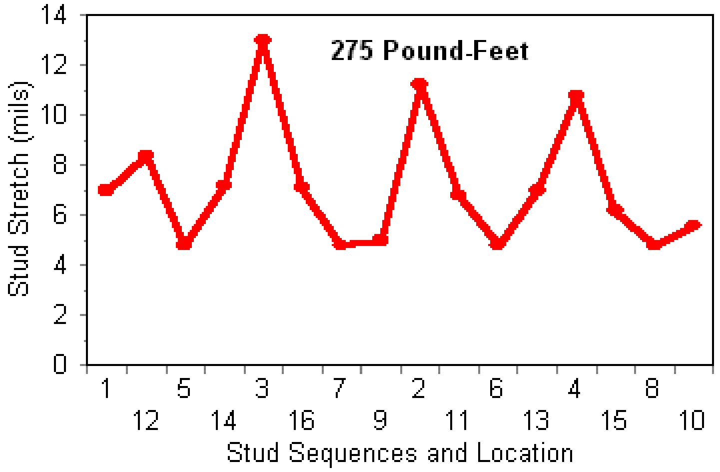
Our experience suggests that the development of a stubborn sawtooth pattern like the one described above is common when a gasketed joint it tightened under torque control. We have been unable to find a torquing procedure that avoids this.

Does a sawtooth pattern of preload mean that the joint will leak? Possibly not if the preload scatter is "slight"; possibly so if the preload scatter is "extreme". Much more work will be required to define "acceptable scatter", if there is such a thing. Meanwhile, all we have to work with are the results from the 94 joints we have so far helped to tighten.



Note: The studs were tightened in a cross sequence. Preload (stretch) was measured after the completion of each pass and therefore after some relaxation had occurred. The final sawtooth pattern is typical of gasketed joints tightened under torque control.

Figure 3--Pattern of Residual Preload Achieved by Applying 100, 200 and 275 Pound-Feet of Torque to Sixteen 1¼-8 x 9 B7 Studs on a 10 Inch, 600 Pound Flange Sealed With a Spiral-Wound Asbestos-Filled Gasket



Note: This figure shows the pattern of residual preload after four additional passes at 275 pound-feet applied in a clock pattern. Note that these "cleanup" passes failed to alter the basic sawtooth pattern created by the initial tightening passes.

Figure 4--Final Pattern of Residual Preload in the Joint from Figure 4

Table 1 summarizes the final results achieved on a representative group of these joints, which involved studs varying in diameter from 1 7/8 to 3 ½ and involved flanges on such equipment as reactors, hydrocracker exchangers, and heaters. All of these joints passed hydrotest, and none of them leaked during subsequent plant operation, even though final preload variation averaged ± 12 percent of the mean and in one case reached 28 percent. Note that the average stress levels, where available, were usually within the 37,500 pounds per square inch permitted by Appendix S of the *Boiler and Pressure Vessel Code*. (The stress permitted varies somewhat with bolt material, temperature, and so forth.)

Once again, however, uniformity in preload is not the only thing required preventing leaks – it may not even be a major factor. Figure 5 is a histogram of sample data for a hydrocracker exchanger joint that did not pass hydrotest. In this case, the studs were 3 ¼ - 8 x 32, B7, with a 25 7/8-inch grip length. C5A lubricant was used.

The studs were originally tightened by applying a uniform torque of 6500 pound-feet to each stud. A selected group was then measured with the ultrasonic extensometer. The mean stretch of the sample was 21.2 mils, with a sample range of –19 percent to +20 percent of the sample mean.

In this condition the joint failed hydrotest. When the joint was disassembled, it was discovered that there were rust particles under the gasket at several locations; these coincided with the leak paths.

The joint surfaces and gasket were cleaned, and the joint was reassembled. This time, 7500 pound-feet of torque were applied, and another smaller sample of studs was measured with the extensometer. The mean preload of this sample was 23.1 mils, with a range of –8 to +12 percent. The size of the sample was so small, however, that these numbers are only a crude guess about the actual mean and scatter of the population.

After these measures were taken, the joint passed hydrotest and subsequently operated without a leak. Note that the final control in this case was torque, not ultrasonics, reminding us that torque is usually sufficient.

It is not possible to say from the data at hand whether success was achieved because of the slightly higher mean preload, the apparently reduced scatter in preload, the cleaning of the joint surfaces, or a combination of these factors, but the fact that the leak paths coincided with the rust particles strongly suggests that the removal of the rust particles was a key factor.

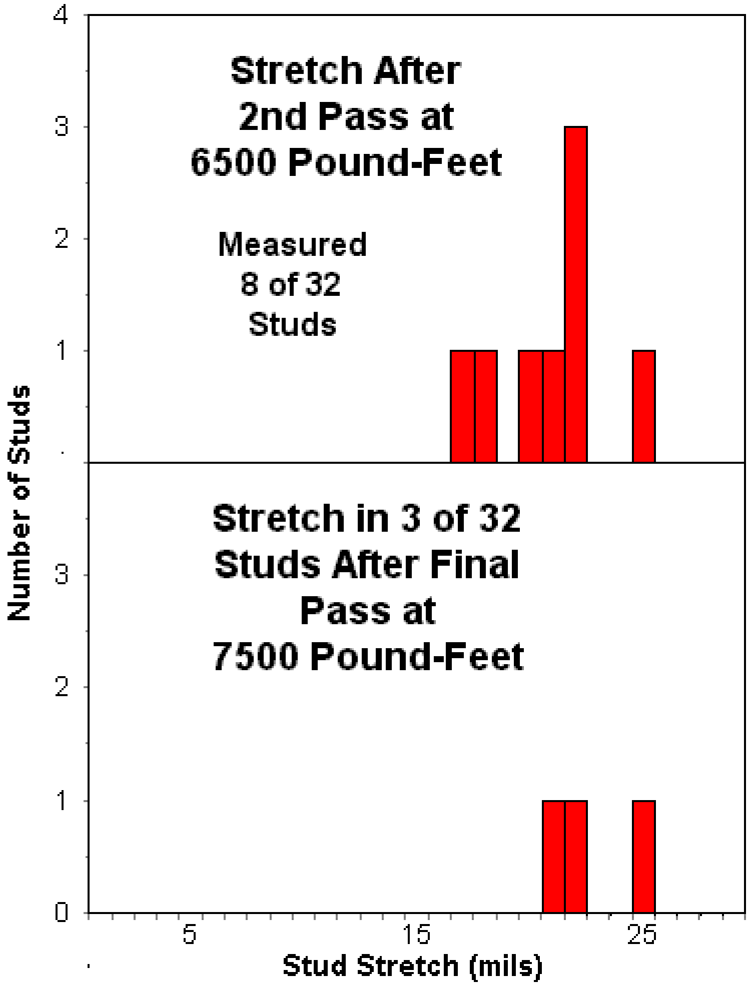
Uniform preload is therefore not the only answer to leak problems, but it appears to be a useful and practical weapon in our war on leaks, at least until better joints and/or torquing procedures have been defined by current studies.

Table 1-- Average Bolt Stress and Scatter Achieved by Ultrasonic Control in a Group of Joints That Subsequently Operated Without Leaking

Bolt Diameter (inches)	Application	Average Stress (psi)	Maximum/Minimum Scatter[1] (percent)	± 3 Coefficient of Varience[2] (%)
1-7/8	Reactor	30,222	-9/+28	
1-7/8	Reactor	32,889	-29/+7	
2-1/4	Reactor (Outer Flange)	20,540	-1.4/+5	
2-1/2	Reactor	33,745	-12/+11	
2-1/2	Reactor	34,582	-14/+6	
2-1/2	Reactor	34,655	-8/+7	
2-1/2	Reactor (top inlet)		-13/+18	
2-1/2	Reactor (pipe to elbow)		-16/+11	
2-1/2	Heater		-17/+24	
2-3/4	Catalyst flange		-13/+15	
3	Hydrocracker exchanger	37,944	-11/+8	
3	Hydrocracker exchanger			±32
3-1/4	Hydrocracker exchanger	38,358		±47
3-1/4	Hydrocracker exchanger			±29
3-1/2	Reactor top	42,556	-1.9/+2	
3-1/2	Hydrocracker exchanger		-14/+16	

[1] If all bolts are measured

[2] if sampled



Note: This joint failed after being tightened at 6500 pound-feet (top panel) but passed after rust particles had been removed from the flange surfacea and the joint had been retightened, under torque control, at 7500 pound-feet (bottom panel).

Figure 5--Histograms of Sample Data Taken After Tightening Thirty-Two 3¼-8 x 32 B7 Studs in a Hydrocracker Exchanger