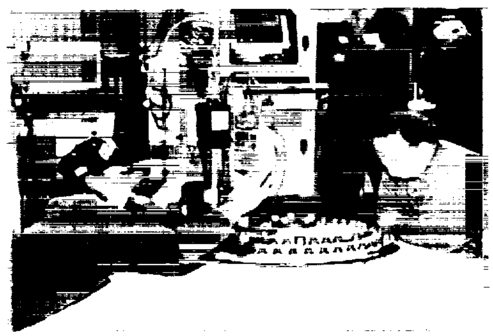
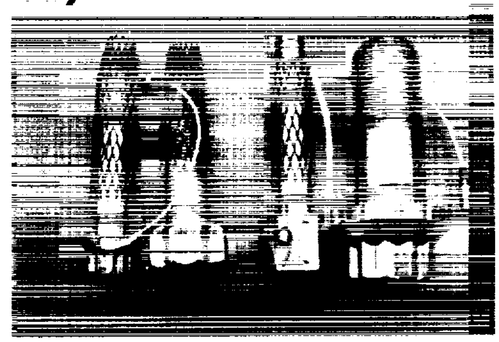
AIAA 2001-36-51

Reducing Bolt Preload Variation With Angle-of-Twist Bolt Loading



Bryce Thompson
Pramod Nayate
Doug Smith
Thiokol Propulsion
Brigham City, UT



AIAA Joint Propulsion Conference
July 9-11, 2001
Salt Lake City, Utah

2001-36-51

REDUCING BOLT PRELOAD VARIATION WITH ANGLE-OF-TWIST BOLT LOADING

Bryce Thompson
Pramod Nayate
Doug Smith
Thiokol Propulsion
Brigham City, Utah

ABSTRACT

Critical high-pressure sealing joints on the space shuttle reusable solid rocket motor require precise control of bolt preload to ensure proper joint function. As the reusable solid rocket motor experiences rapid internal pressurization, correct bolt preloads maintain the sealing capability and structural integrity of the hardware. The angle-of-twist process provides the right combination of preload accuracy, reliability, process control, and assembly-friendly design. It improves significantly over previous methods. The sophisticated angle-of-twist process controls have yielded answers to all discrepancies encountered while the simplicity of the root process has assured joint preload reliability.

Pressurized joint component deflection controls O-ring or gasket function, and thus joint sealing capability. A tight joint will seal acceptably to lower temperatures than a looser one will. Deflection control requires precise bolt-clamping force (preload). Several methods for preloading critical fasteners have been used over the years. Design requirements, flight environments, and manufacturing concerns have driven the bolt preload to a narrower range of variation than that afforded by traditional torque methods. Angle-of-twist provides accurate preload without the need for overly complex, difficult-to-diagnose/verify, or difficult-to-control process alternatives.

Previous bolt loading methods resulted in a preload variation of ± 35%. This variation level was too high to ensure minimum preload and avoid overloading the joint at the same time. An ultrasonic loading method was implemented in an effort to resolve the issue. The ultrasonic process on the assembly line revealed that variations of ± 35% or higher could occur on an infrequent basis. Thiokol invented the ultrastrain bolt to simultaneously measure preload with 1% strain gages. The AOT process was implemented with significantly reduced joint preload variation (± 12 % to ± 19% depending on joint type vs. ± 35% for torque).

Changes in Space Shuttle launch commit criteria, the ability to tolerate higher component wear/damage, and the elimination of elusive ultrasonic discrepancy reports have resulted from the AOT process. AOT torque limits are currently being fine tuned to better reflect flight torque populations. This will reduce torque related discrepancies that do not impact preload while continuing the excellent preload performance of AOT.

INTRODUCTION

There are three critical bolted joints on the space shuttle reusable solid rocket motor (RSRM) that require a reliable method of bolt loading. These joints are the igniter inner joint, the igniter outer joint (Figure 1), and the nozzle-to-case axial/radial joint (Figure 2). The bolt-preload requirements for these joints are pivotal to maintain the sealing capability, and the structural integrity of the hardware during the rapid pressurization of the motor. In order to maintain a seal, the initially compressed seal material must expand to fill the larger volume created by the increasing distance between seal surfaces. A safe design is achieved when the opening of the gap between seal surfaces is less than the capability of the seal to expand, maintaining structural integrity of the hardware.

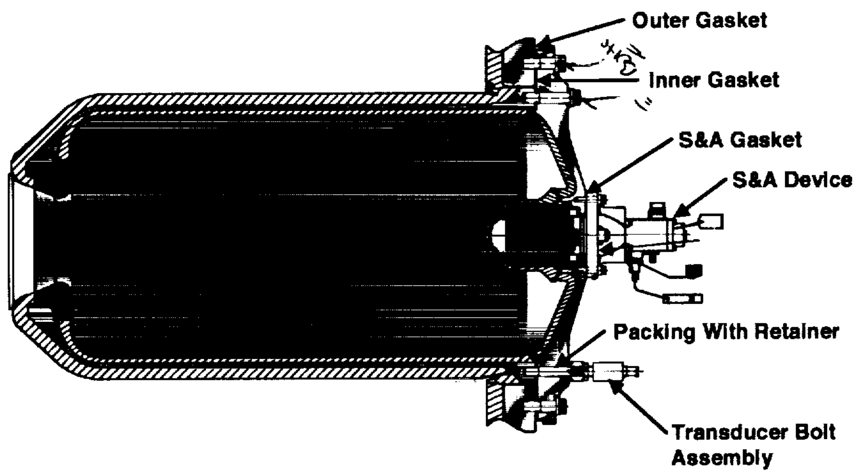


Figure 1. Ignition Joint Seal Performance

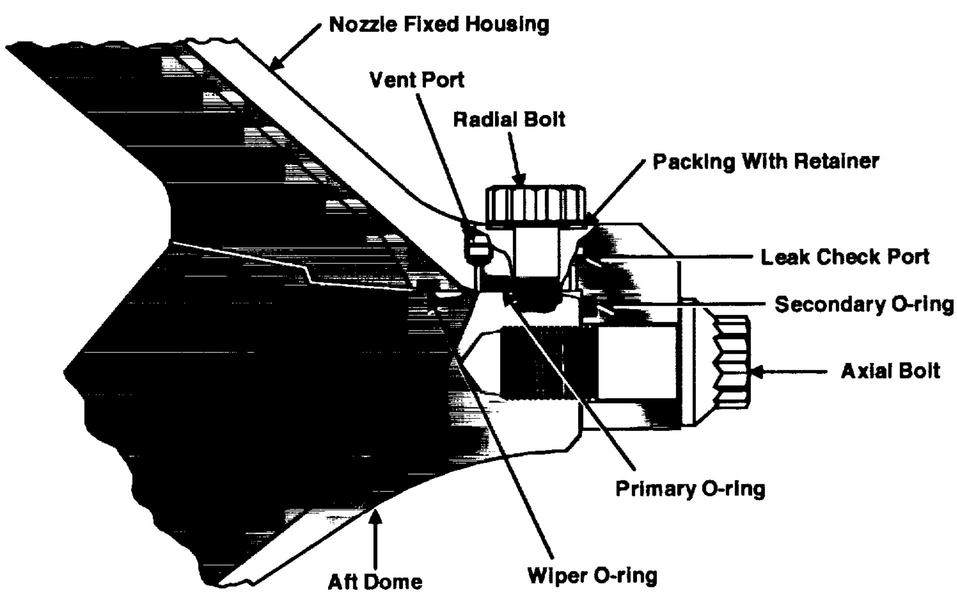


Figure 2. Nozzle-to-Case Joint Performance

Bolt loading was torque dependent in the past. The bolt load variation was too high (±35%) to ensure a minimum bolt preload and avoid over loading of the joint at the same time. Later another bolt loading method (ultrasonic bolt loading) was applied. The ultrasonic process on the assembly line revealed that variations of ± 35% or higher could occur on an infrequent basis.

Thiokol invented the ultrastrain bolt to simultaneously measure preload with 1% strain gages. AOT was then developed with the following objectives:

1) Simplify the loading process such that anomalies are clearly understood
2) Provide thorough, automatic controls of process variation such that bolt preload is delivered accurately and verifiably

The currently used AOT bolt loading method produces low bolt preload variation maintaining the sealing capability and the structural integrity of the joint. The AOT method consists of tightening a bolt to "snug torque," and then continuing to tighten until a predetermined angle is achieved. The snug torque is the torque value that ensures that the joint components are clamped together and that all mating surfaces are in full contact. Further tightening of the bolt causes it to stretch and the other components to compress, inducing the preload. Two parameters are recorded during AOT (torque and angle). Torque is subsequently plotted versus angle in order to assess the integrity of the joint loading. The design preload is achieved by the angle of rotation while torque is a function of hardware and process variations. Torque angle curves for each joint were developed. The final angle requirements must be met while staying within the torque angle bounds established (Figure 3).

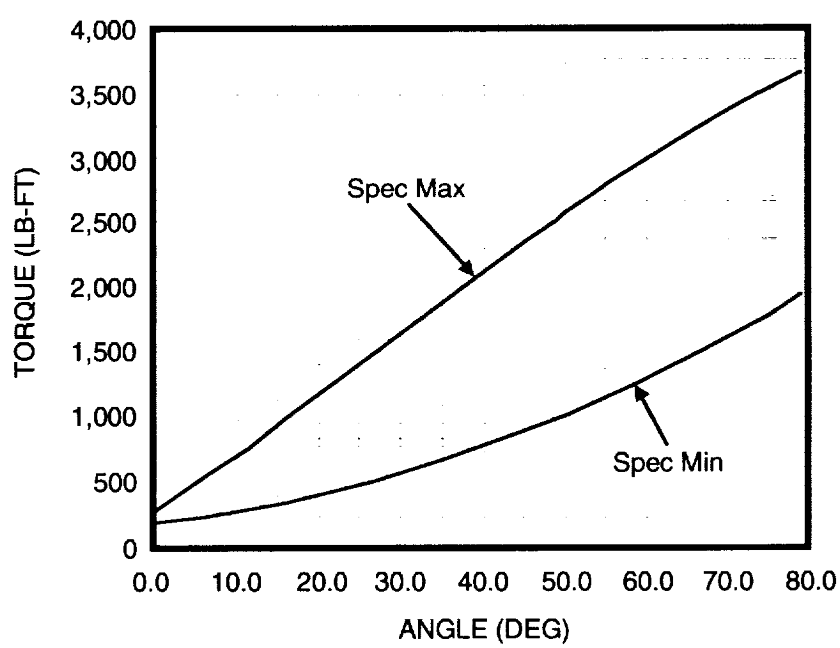


Figure 3. Torque-Angle Curves (upper and lower limits)

Extensive testing was performed to determine optimal snug torque and angle of rotation of the bolt for a given joint. Bolt torque, angle, and preload of the ultrastrain attach bolts were monitored to evaluate the process variation and determine loading uncertainty. It has been demonstrated that AOT provides an economical, reliable, and relatively simple bolt loading method. Many problems involving hardware and process were identified using AOT without which the problems would have remained unidentified.

A bolthole was originally machined crooked on a forward dome, for example. The abnormal looking torque/angle curve indicated that there was a problem (Figure 4) with the joint. This result contrasts sharply with torque or ultrasonic loading methods. The thousands of tests performed on each bolt-loading offer a simple, easy to understand method of controlling process.

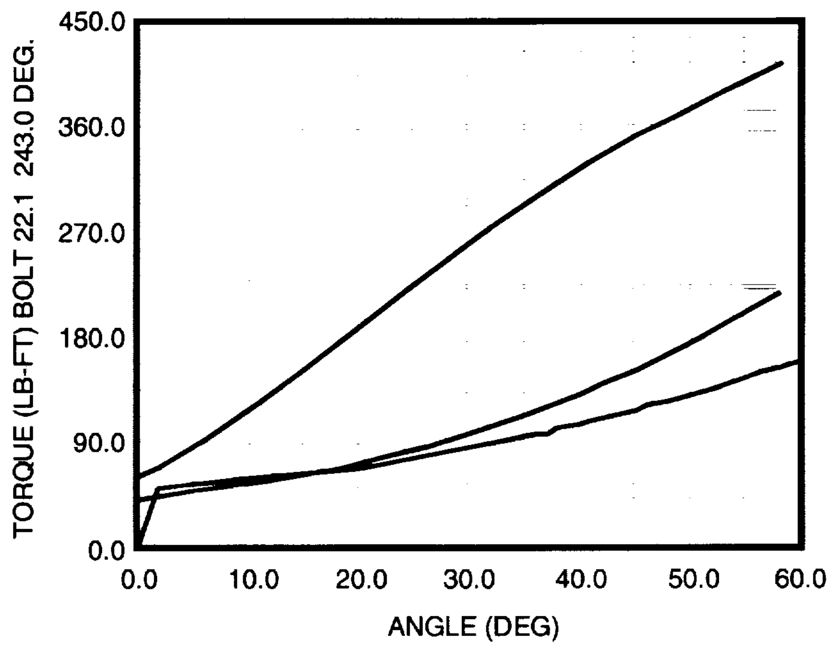


Figure 4. Abnormal Torque/Angle Curve

ULTRASTRAIN (UST) BOLTS

The UST bolt was developed by Thiokol to meet several objectives simultaneously. A 1% accuracy requirement on preload while ignoring torque, head bending, and temperature effects. It had to have a minimum impact on stress/strain properties during AOT in order to simulate flight bolt AOT performance. The design also needed to be rugged enough to survive repeated use in a manufacturing environment.

A shallow circumferential groove on the UST bolt shank contains four strain gages at equal angular intervals wired as a full-bridge transducer. The gages are arranged to be insensitive to shear plane motion in torsion, and to cancel axial bending effects exactly. Temperature compensation is maximized by mounting the full bridge in close contact with the bolt shank. The groove that holds the strain gages is cut to a depth less than that of the bolt thread. The groove's small width and depth has negligible effect on bolt preload as generated by AOT shank strain. The strain gage leads are brought out of the bolt head through a narrow axial passage and an axial groove cut at the same depth as the circumferential groove (Figure 5).

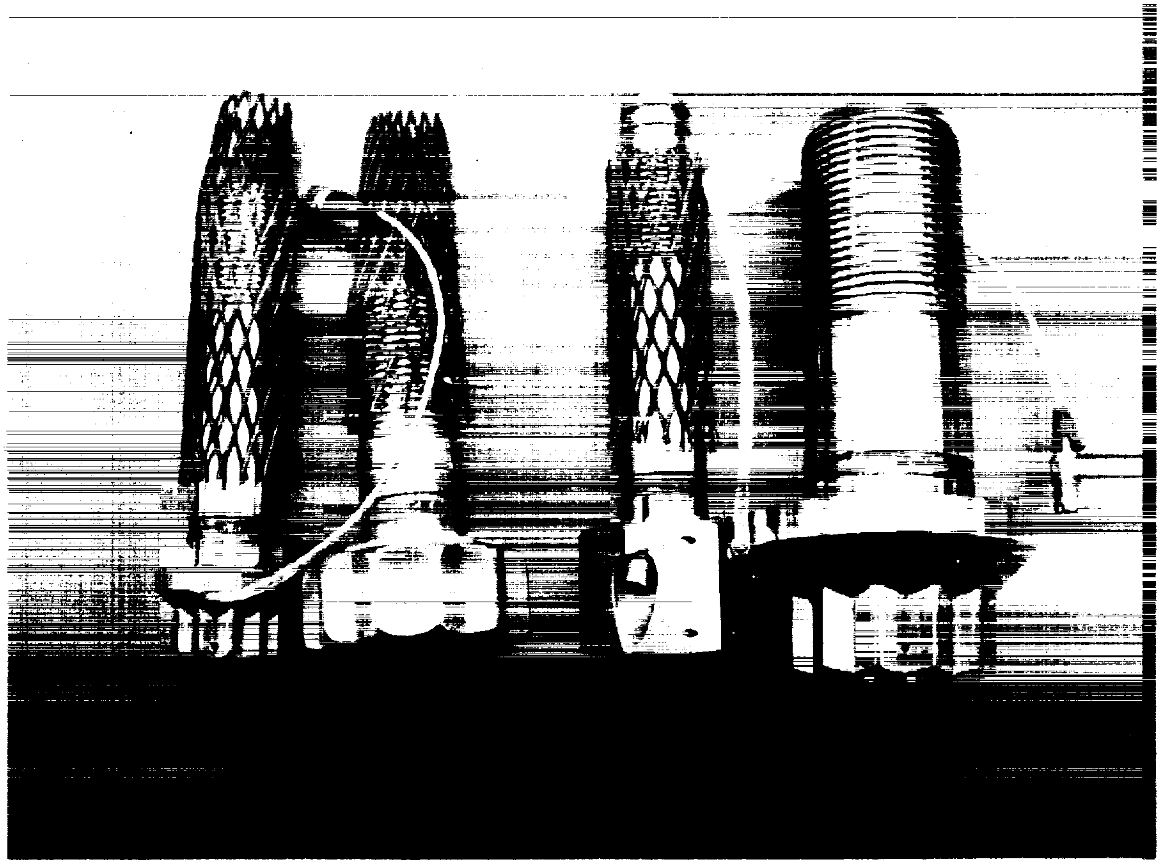


Figure 5. UST Bolt

DISCUSSION

Setting up an AOT process starts with an assessment of the optimal snug torque-to-angle transition. AOT first measures torque as loading begins. It automatically transitions to angle once snug torque is reached. It completes loading to a final angle and then shuts off the motor drive. The interaction of torque and angle to yield preload in an AOT process is shown on Figure 6. Torque alone yields ± 35% 3-sigma bolt preload variation. Bolt angle alone yields high preload variation due to large changes in joint spring constant prior to effective clamping. An AOT system combines these two methods. The system drives a given bolt to a "snug torque" level. This establishes a small portion of the final preload (± 35%). It provides a point for angle to start that has a fairly controlled joint spring constant. The snug torque level is determined by minimizing final

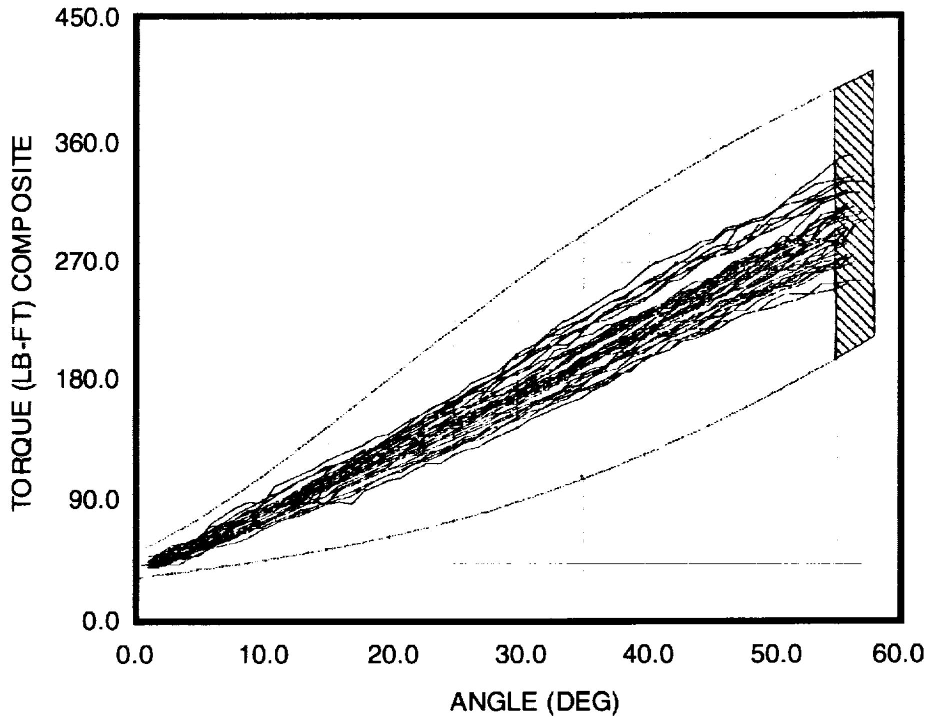


Figure 6. Interaction of Torque and Angle to Yield Preload in an AOT Process

preload variation (statistically). Angle takes over dynamically from torque as the preload driver at the snug torque level. There is less uncertainty and greater control with dynamic torque preload. Preload varies linearly with angle at about ± 6% 3-sigma variation from snug torque to final angle. The root sum squared variation contributions from snug torque and angle allows the typical ± 15% 3-sigma AOT performance (joint-dependent). Note the upper and lower torque limits shown on the AOT computer loading display (Figure 7).

Excursions beyond the limits automatically shut down the tooling (real-time quality control). These limits as a function of angle were statistically determined from test data. The upper limit is designed to prevent the AOT tool from damaging threads in a high torque condition. Knowledge of a normal torque profile helps us here by shutting off an abnormal loading before it reaches the point of thread damage, or bolt galling. The lower limit is designed to catch a soft joint condition. AOT depends upon a fairly uniform stiff joint spring constant at the snug torque level.

Abnormal hardware or assemblies can cause a loss of preload. The lower limit flags this condition. Threaded holes with excessive tapered pitch diameter are individually screened to assure a proper preload. A tapered hole pitch diameter is caused by reuse and rework of threaded holes. This is a significant effect with the RSRM. The taper causes a lengthening of the bolt effective grip length and thus a lowering of preload. Control of thread wear is thus achieved through screening of extreme cases.

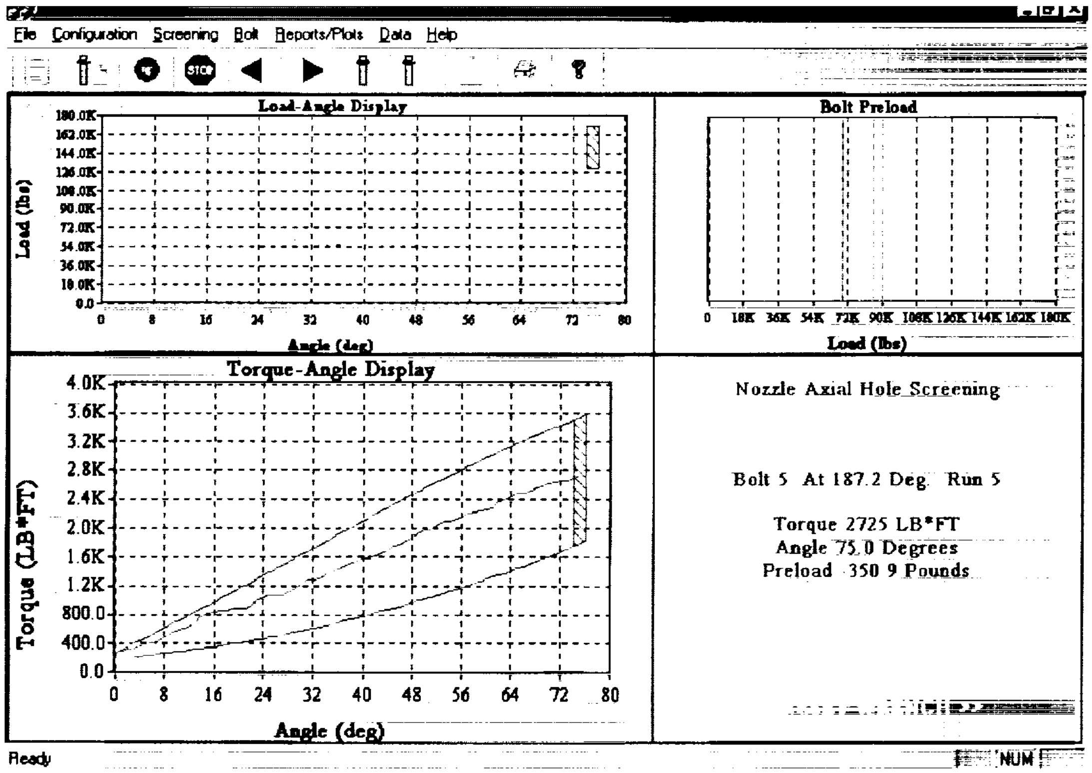


Figure 7. AOT Computer Loading Display

The following issues have been resolved with the automatic controls used by Thiokol's version of the AOT process:

- Radius of washer was interfering with the bolt shank radius. The interference was causing the washer radius to deform instead of stretching the bolt. The torque/angle curve showed unusual behavior. The washer design was modified to eliminate this problem.

- For a successful joint leak check, it is important that the bolt load does not exceed certain bolt load. In this case it was determined to be 25 ft-lb maximum. The torque/angle curve indicated that the initial torque was 80 ft-lb. This condition would have masked the leak check. Without the AOT bolt loading method, this condition would have gone unnoticed.

- One of the boltholes was mismachined. The bolthole axis was about 2 degrees with respect to the perpendicular. Since the hole was crooked, one edge of the bolt head was digging into the dome instead of stretching the bolt. This condition was noticed because of unusual nature of the T/A curve (Figure 4).

- For efficient and successful bolt loading, it critical that the lubricant is applied correctly and on the load bearing surface of the bolt. The T/A curve showed an unusual behavior and further analysis showed the incorrect lubricant application.

- During bolt loading, the T/A curve showed an unusual behavior, the torque was close to the low end and was somewhat flat. Further investigation showed that the bolthole was like an inverted cone (the second thread pitch diameter was larger then the first thread pitch diameter, the third thread pitch diameter was larger than the second thread pitch diameter, etc.).

- The operator accidentally tried to load the previously loaded bolt. The T/A curve immediately jumped out of the upper limit, causing the motor to stop. This saved the potential damage to the hardware.

- Many defective (flatness violation, pitting, etc.) hardware previously could not be used due to the wide preload variation. But with the narrower range of the bolt loads due to the AOT bolt load method, some of them could be used, saving a significant amount of cost to manufacture this complex hardware.

SUMMARY

The most direct (and accurate) method of preload assessment is through the use of strain gages on each bolt. Processing the bolts is expensive. Furthermore, the process is hard to set up and use because calibration factors and individual pedigree for each bolt must be established and maintained.

The AOT method is not as accurate as direct strain gage readout. Setup is extremely easy—the wrench runs and shuts itself off. Cabling setup and software operation subtract a little from the rating. The simplicity of the basic process makes preload verifiability virtually certain.

Manufacturing friendliness is high yet reduced due to the torque limits. The limits have caught many situations as mentioned above. They can be overly tight, however. This has caused some loading issues that were not preload related. Because of the narrow load range (± 15% typical) maintenance of seal integrity and structural integrity has significantly improved. Because of torque limits established for each angle, any defect in the joint gets noticed and the loading process stops if the limits are exceeded. This also helps to avoid any damage to the hardware.

Torque method accuracy is very unpredictable. The preload uncertainty may be 35 to 40%. The error distribution is often not "normal." Entire joints may shift instead of demonstrating a randomly distributed normal error. Computer software screens and visual assessment of the joint torque- angle data allow a thorough assessment for each bolthole and joint to be performed prior to acceptance of the operation.