Berkeley Engineering and Research, Inc.

PLURES INTELLIGENS MODICUM MACHINATOREM

Gall Thomson Connecter Release
Hawaii Single Point Mooring Terminal
May 19, 2006

for

Tesoro Corporation
300 Concord Plaza
San Antonio, TX 78216

August 30, 2008

by

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Executive Summary

On May 19, 2006 at 23:20 hours, a Gall Thomson marine breakaway connector (GTC) in a floating hose released unexpectedly during the offloading of the ship *Front Sundra* at the Tesoro Hawaii single point mooring (SPM). The analysis clearly indicates the GTC release resulted from the combination of three causes:

1) **A new breakstud preload procedure.** The new procedure (Appendix A) produces higher preloads which in combination with Cause (2) is detrimental to breakstud fatigue life. The new procedure also relies on electronic strain gages to determine preload. While strain gages can be very accurate, they are also unreliable and may have distracted the installers from adequately performing important assembly fundamentals (e.g. tracking breakstud and nut rotation).

2) **A breakstud design that is highly susceptible to fatigue.** The Gall Thomson breakstud design details (see Appendix B - "*Breakstud Design Drawings*") are contrary to standard textbook recommendations for reducing the likelihood of fatigue in bolted connections: (i) the small radii at the ends of the reduced section increase stresses by as much as a factor of 3; (ii) the relatively rough reduced section surface finish can decrease the titanium material fatigue strength by as much as a factor of 5; and (iii) the short length of the reduced section unnecessarily increases the portion of cyclic wave loading passing through the breakstuds instead of the flange, results in little elastic stretch at the design preload and large variations in preload for small differences in torque and nut rotation.

3) **Lack of a proper "Fitness For Service" evaluation**. The manufacturer, Gall Thomson, has never performed a stress/fatigue analysis appropriate for the subject service, nor a risk assessment indicating this device actually lowers the risk of a spill. Gall Thomson, has stated in correspondence [17] that the GTC is "*immune from fatigue*" as long as the breakstuds are properly preloaded. This is simply incorrect. FaAA (Exponent), in their analysis and redesign of the breakstuds, correctly concluded that the stresses are extremely high at the small radii and "*the primary source of cyclic loading on the GTC in service is wave induced bending . .*". A detailed fatigue analysis including the design details in Cause (2) above, however, was not performed.

There is no indication of external impact or any other damage that might suggest additional causes. The weather at the time of the incident was relatively calm. Also, the Hawser load measurements and field observations do not indicate the ship drifting and exerting excessive load on the hoses and connector.

The hydraulic analysis, which was conducted using the crude oil flow rate at the time of the incident, indicates that inadvertent valve closure at the terminal could not have produced pressures high enough to separate the connector. The peak calculated pressure at the GTC is 280 psi, significantly less than the 450 psi necessary to cause a connector release.

The fatigue damage on 4 of the 8 breakstuds precludes overload type events (e.g. hydraulic transients and impact) as being primary causes of failure. The fatigue analysis performed by BEAR, using local wave loading data from the past 3 years, indicates a lower bound service life for the current design of approximately 1 year, with an expected life in the 3-5 year range. Upgrading the breakstuds by changing the radius to an exponential shape and specifying a surface roughness of 16 AA or better, results in a calculated infinite life if preloaded to the currently specified 5,150 lbs and a life greater than 7 years if the preload is lost.

BEAR worked with Gall Thomson, FaAA and Tesoro Hawaii, in specifying upgraded bolts for the anticipated changeout this September. The changes, agreed to by all parties, are given in BEAR drawing 06-2447G-1. The reduced section radii are to be increased from 1/32 to 1/16 inches and the surface roughness is to be 16 AA (micro-inches) or better. These changes have resulted in Gall Thomson moving from grinding to a computerized numerical controlled (CNC) machining method of forming the reduced section. With a CNC method of manufacture, the stress concentration factor at the reduced section radius can be reduced to approximately 1.0 by using an exponential shape discussed in the report.

Short Term Recommendations: (i) implement a bolt-up procedure with more checks and balances (e.g. tracking torque, nut rotation, and stud rotation) and (ii) employ a more robust breakstud design as described above.

Long Term Recommendations: Tesoro should consider removing the connectors from the SPM hose system. The devices are by design a weak link, and they will always retain some risk due to manufacture, handling, installation, and/or abuse in operation. Furthermore, the design details and documentation indicate that the connectors have not undergone a thorough stress, fatigue and fracture analysis adequate for the intended service.

The recommendations given in the 1989 Coast Guard Report (Appendix C) to reduce the risk of an oil spill at the SPM resulted in the implementation of a large number of safety precautions (e.g. 24 hour surveillance monitoring, a 4,000 horsepower tug tethered astern, 24 hour hawser load monitoring, etc.), described in detail in the SPM Handbook. The report does not recommend a breakaway coupling. Recommendation No. 5 states:*"provide the means of rapid cargo hose removal"*. There are several quick release devices on the market with excellent field experience (e.g. the Quikcon by FMC Energy Systems). The Quikcon coupling is being used at Tesoro's Alaska wharf. These devices have the added advantages of attaching to any common style flange (Metric, ANSI and BS), not requiring bolt hole alignment, and having a built in gasket as well as being easily releaseable with a standard wrench/spanner. They would meet the intent of the Coast Guard recommendation without the risk of accidental releases.

Assuming that Tesoro continues to use the connectors, BEAR also recommends the following breakstud improvements: (i) employing a larger profiled radius as described in Section 5.1 of this report, to further reduce stresses and make the surface finish more inspectible; (ii) increasing the length of the reduced area section; (iii) specify CNC manufacturing instead of grinding; (iv) hydraulic stud preloading and (v) strongly consider eliminating the strain gages.

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1.0 Background

On May 19, 2006, Tesoro Hawaii Corporation (Tesoro) experienced an accidental release of a 12 inch marine breakaway coupling in a floating hose transporting crude oil. This was the fourth accidental or unexpected release since 1999. Berkeley Engineering And Research, Inc. (BEAR) was requested by Tesoro to perform an independent evaluation of the breakaway couplings.

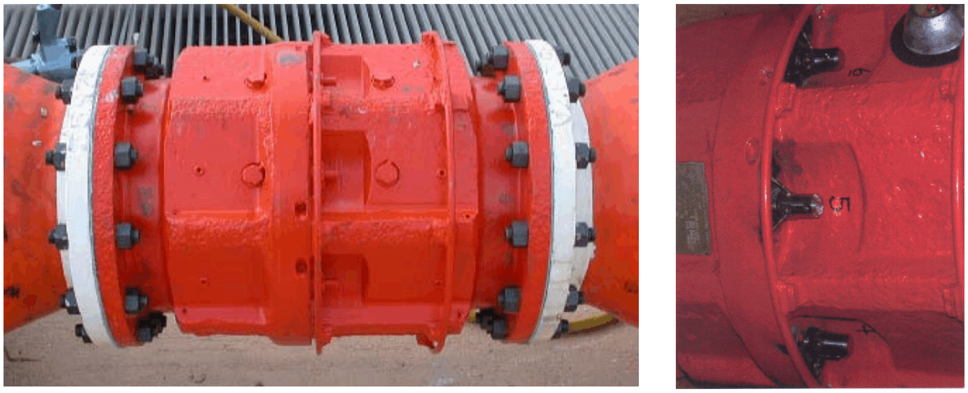
1.1 The Single Point Mooring Terminal

Tesoro Hawaii Corporation loads and unloads petroleum tanker ships utilizing a Single Point Mooring Terminal (SPM) located 1.7 miles offshore near Barber's Point, Oahu, Hawaii. The system consists of: (i) three marine cargo pipelines (16 inch bunker line, 20 inch white products line and a 30 inch crude line) that run to/from an onshore terminal which is part of Tesoro's Hawian Refinery; (ii) a buoy and ship mooring system; and (iii) 3 flexible hose strings permanently attached to the buoy that can be attached at the other end to any tanker ship moored at the SPM, see Figure 1.

Figure 1. The Tesoro Hawaii Corporation Single Point Mooring Terminal (SPM)

1.2 The Breakaway Connectors

Each of the 3 flexible hose string contains a marine breakaway connector (GTC) manufactured by Gall Thomson, Ltd. of Norfolk, England, see Figure 2. The GTC consists of two halves, bolted together with 8 specially designed bolts or breakstuds that are designed to fail a specified load, 25 tonnes for the Tesoro SPM hose strings.



Figures 2a and 2b. Gall Thomson breakaway in a hose string on left and closeup of installed breakaway studs on the right.

The specially designed studs are made of a titanium alloy, nominally 5/8 inches in diameter with a reduced diameter section in the center. The reduced center section diameter is sized (approx. 1/4 inch) to breakaway at the specified load. Figures 3a and 3b show the breakaway studs before and after FaAA's design modification to include electronic strain gages, respectively.

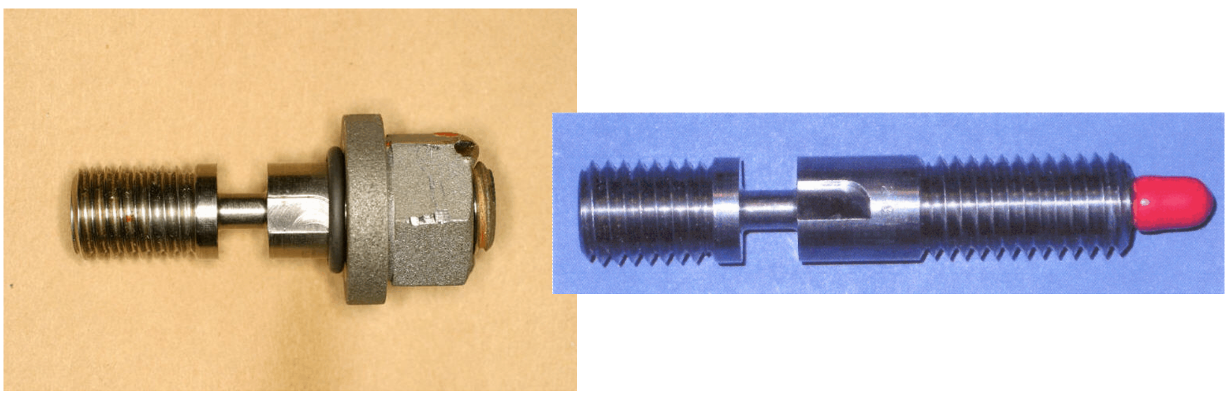


Figure 3a and 3b. The breakaway studs before (left) and after the design modification to include strain gages (right). The red tip covers the strain gage electrical connection.

FaAA was hired by Tesoro to provide an independent evaluation of the GTC breakstud preload after the third GTC release in 2001. FaAA performed a complex nonlinear finite element analysis of the GTC and recommended installing electronic strain gages in the breakstuds to more accurately set the breakstud preload. Design drawings for the breakstud before and after the FaAA are given in Appendix A, "Breakstud Design Drawings". The radius at each end of the reduced section, 1/32 inches was retained in the FaAA design. Neither design drawing specifies radii tolerance or surface finish.

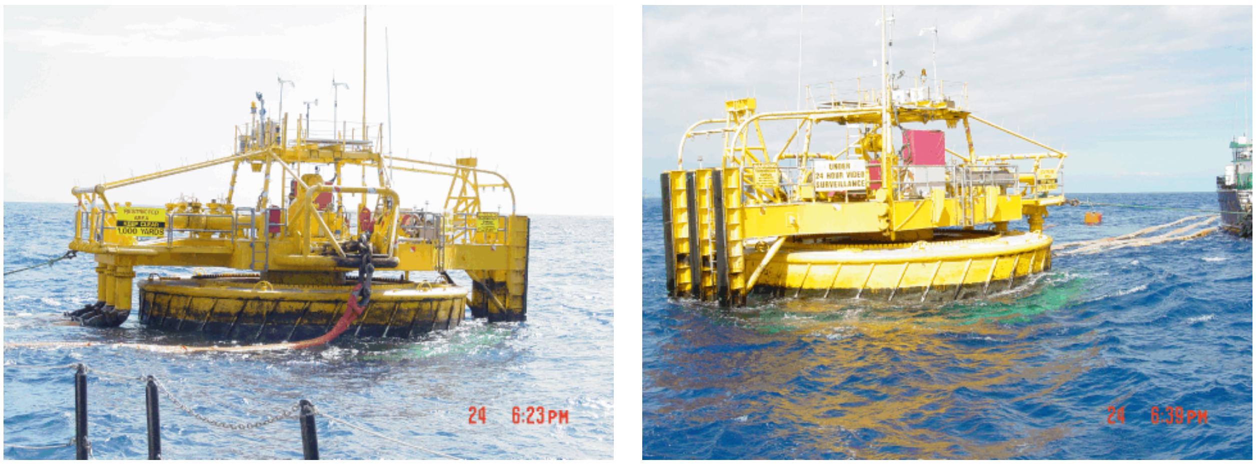
1.3 History of the Breakaway Connector at the Tesoro SPM

The connectors were initially installed in 1993 in response to a 1989 incident in which a ship broke loose from the SPM, ruptured a cargo transfer hose and grounded just off Barber's Point. The Coast Guard's report on the incident, given in Appendix B, "*1989 Coast Guard Report*", recommended several improvements to the SPM system. It did not recommend the use of breakaway connectors, only "*a means of rapid cargo hose removal*". Additional historical data on the prior GTC failures are given in the "*Gall Thomson Timeline*" assembled by FaAA and is provided in Appendix D, "*GTC Timeline*".

Besides the breakaway connectors, numerous improvements were made to the SPM system and transfer operations to significantly reduce the risk of an accident as described in the Tesoro SPM Handbook [1]. The improvements include: (i) load monitoring of the hawser (main ship mooring line to the buoy system), (ii) 24 hours/day low light TV/infrared surveillance of the SPM, (iii) transfer of two qualified Mooring Masters to the ship while at the terminal, (iv) requirement of the ship to maintain live watches at the bow and transfer manifold and (v) a 4,000 horsepower stern tug tethered astern of any moored vessel at all times while at the terminal.

2.0 Field Inspection

On May 24, 2006 the author of this report traveled to Hawaii, met with Tesoro personnel and inspected the SPM buoy. The following 2 days were spent inspecting the onshore piping and terminal, the ship offloading crude at the time of the incident, the *Front Sunda*, and the subject Gall Thomson Connector, GTM0645.



Figures 4a and 4b. The Tesoro single point mooring (SPM) buoy.

The 3 floating hoses can be seen in Figures 4 and 5. The hawser, used to tether a ship to the buoy, can be seen in Figure 4a, attaching to center/midline of the buoy. A Gall Thomson breakaway connector can be seen in Figure 5, in the furthermost hose string.

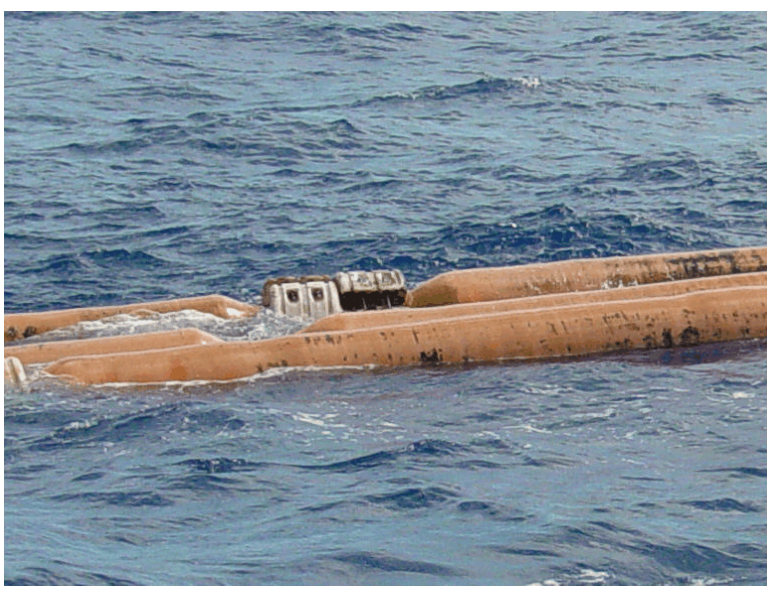


Figure 5. Photograph of the 3 floating hoses. A GTC can be seen in the furthermost hose.

The subject GTC, GT0645, is shown below in Figures 6 and 7 while still in Hawaii. The breakway flange in the center of the unit had come apart or released. There is a shutoff valve in each half of the unit to minimize the loss of hydrocarbons into the ocean. One of the shutoff valves can be seen in Figure 6; it consists of 8 triangular-shaped sections, or fingers, that rotate toward the center and create a seal. The silver-colored, stainless steel sleeve, visible in Figure 6a, holds open the spring-loaded shutoff valve fingers when the GTC is in normal operation.

Figure 6a and 6b. The subject GTC in Hawaii. Both halves are shown in 6a. The shutoff valve in the ship end of the GTC can be seen in 6b.

The two halves of the GTC are held together with 8 titanium breakaway studs. The studs have a diameter of 5/8 inches on each end. The middle section is ground down to approximately 1/4 inch in diameter (see Figures 2 and 7) so that the stud will breakaway at the design load.

Figure 7. Closeup of a broken breakaway stud (center of picture) in the subject GTC.

Numerous photographs and video recordings were taken to document the *Sunda's* pump and piping system and record any signs of damage due to the incident. The *Front Sunda* is shown in Figure 8. The port side manifold is shown in Figure 9.

Figure 8. The *Front Sunda*, port side.

Figure 9. Transfer manifold on the port side of the *Sunda* (looking toward the bow), approximately midship, in front of the deck cranes in Figure 8.

The field inspection trip is documented in a letter/report from BEAR to Tesoro, dated July 14, 2006 [2]. A DVD containing the video recordings made, and a CD containing all pictures taken and scanned copies of all documents, drawings provided and documentation of damage on the *Sunda*, were included with the letter/report.

3.0 Hydraulic Transient Analysis

A hydraulic analysis was performed using the crude oil flow rate at the time of the incident to determine if an inadvertent valve closure at the terminal could have produced pressures high enough to separate the connector. A peak flow rate of approximately 18,000 barrels/day was estimated from the difference in pressure readings at the buoy (Tesoro P&ID designation: PI3410) and onshore terminal marine manifold (PI2332). The flow rate was confirmed via onshore tank readings.

Using BEAR's hydraulic transient program, FluidHT, pressure transients were calculated at the GTC and onshore terminal motor operated valve (MOV2207) for various closure times of MOV2207.

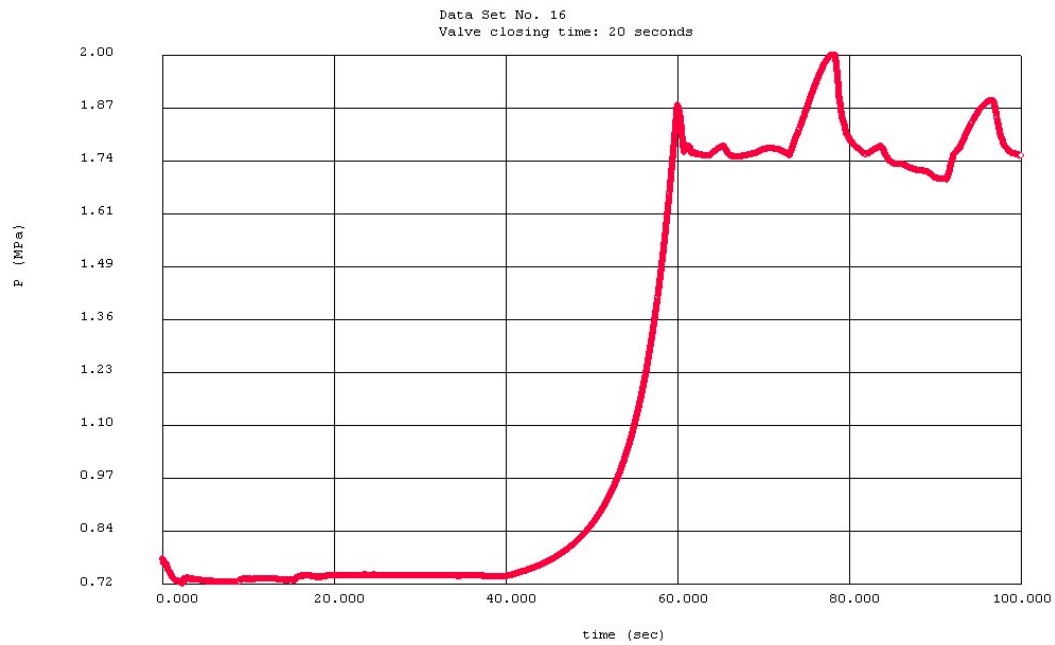


Figure 10. Pressure transient at the GTC for a 20 second onshore terminal MOV close time.

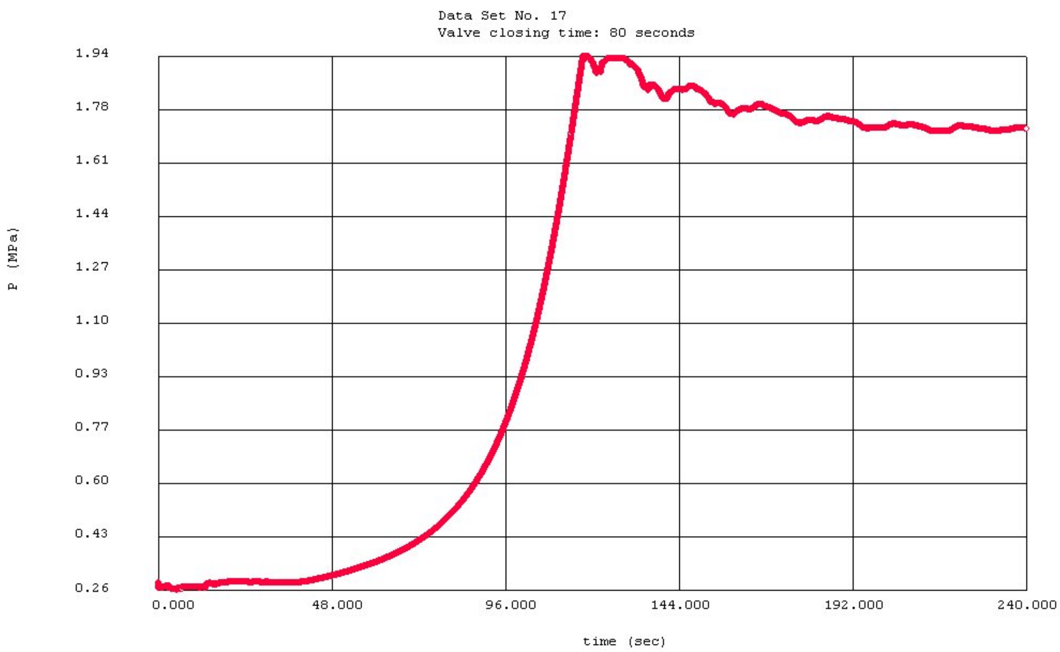


Figure 11. Pressure transient at the GTC for a 80 second onshore terminal MOV close time.

The minimum close time for the onshore MOV is 20 seconds. The hydraulic transient for 3 second closure at the GTC was also calculated (see Figure 12). The shut off valves in the GTC were set by Gall Thomson to close in 3 seconds.

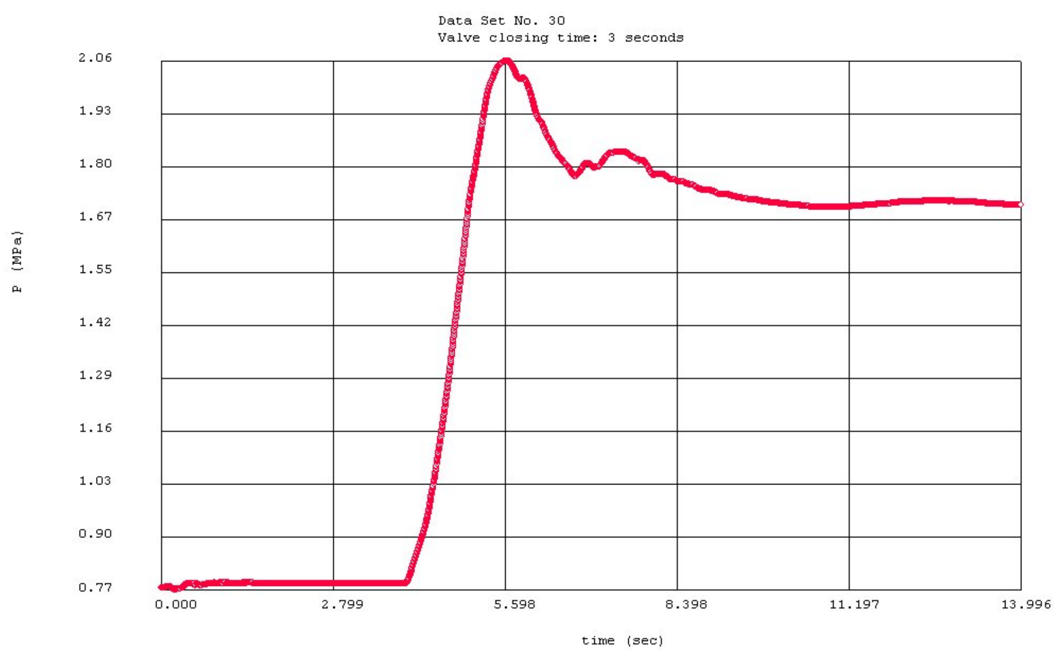


Figure 12. Pressure transient at the GTC for a 3 second GTC valve close time.

A summary of the results are shown in Figure 13 below. Peak pressure at the GTC and onshore MOV are given as a function of valve close time (solid and dashed lines in Figure 12). The peak pressure at the GTC was also calculated for a 3 second close time at the GTC (circle with a dot in center). None of the calculated pressures are near the 450 psi necessary to cause a connector release. It should be noted that the pressures experienced at the ship would be lower than the values presented in Figure 12.

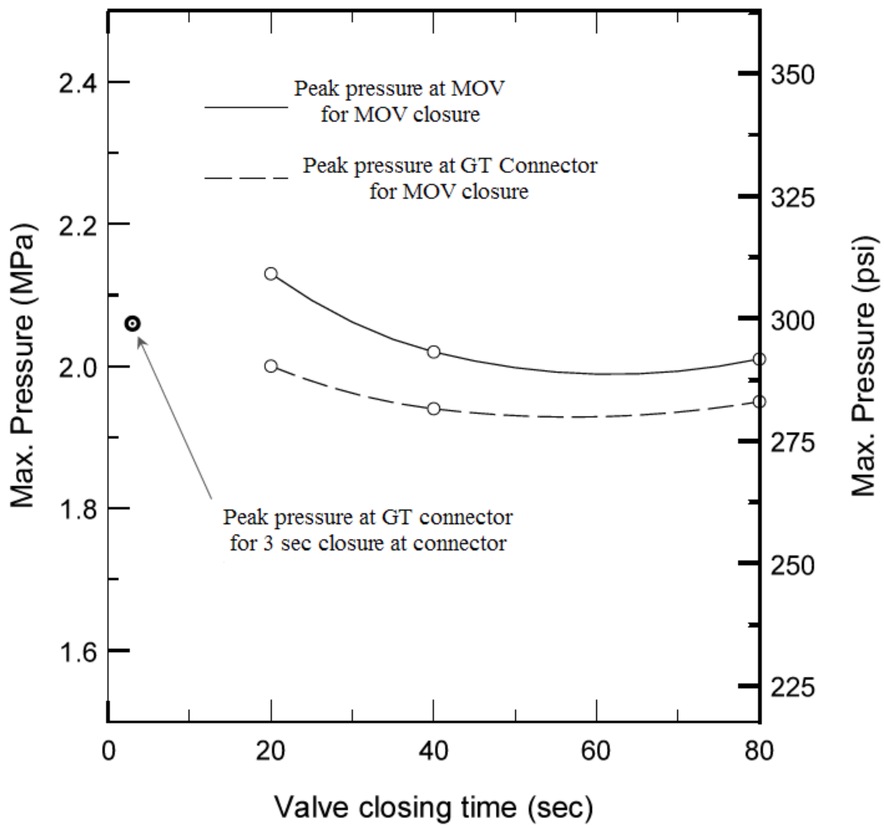


Figure 13. Hydraulic transient peak pressure results. Peak pressure for closure at the GTC connector in 3 seconds (single point). Peak pressure at the terminal MOV (solid line) and at the GTC connector (dashed line) as a function of MOV closure time.

Additional information on the ship and terminal piping, drawings, pictures and video clips, pressure recording printouts and tank gauging records were transmitted to Tesoro in BEAR field inspection, Trip Report [2].

4.0 Metallurgical Analysis

An extensive metallurgical assessment was carried out by BEAR. The results were transmitted to Tesoro in a report dated July 25, 2006, "Metallurgical Analysis of Gall Thomson Connector Breakstuds" and a supplemental report dated August 20, 2006 [3]. The conclusions reached in those reports are listed below for convenience:

CONCLUSIONS

1. Breakstuds #1, #3, #4 and #8 failed due to fatigue cracks that initiated at grinding marks in the radius area.

2. The other four breakstuds failed in a ductile manner at the center of the reduced-diameter section.

3. The fracture of breakstud #1 has the following unique characteristics, which suggests that it was the first to form fatigue cracks:

    Oxidation of the fatigue zone is darker than the others, suggesting that it had been exposed for a longer period of time than the others.

    The fatigue crack zone is relatively large in comparison to the others and is at a markedly different inclination than the others.

    It does not exhibit necking at the center of the reduced-diameter section, while the others do.

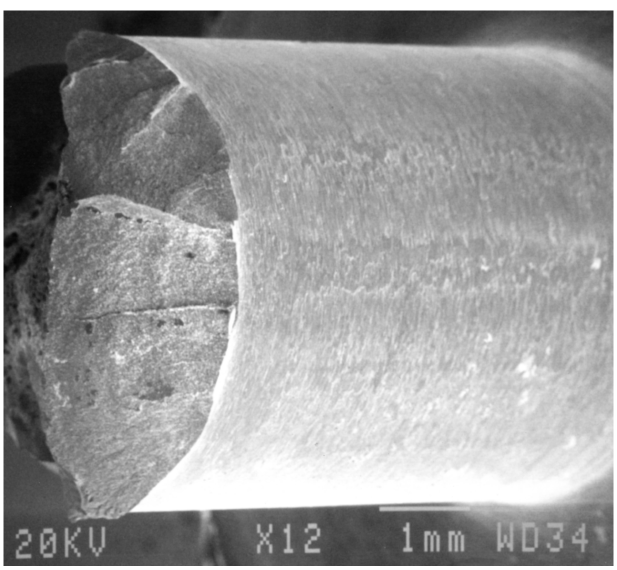
    The surface finish of the reduced-diameter section displays layers of smeared metal riddled with cracks. The degree of smearing exhibited by breakstuds #3 and #4 is considerably less pronounced in comparison.

4. Breakstuds #3, #4 and #5 exhibit witness marks from the peg to indicate that they had at one time been in the proper position but had since rotated. These marks are consistent with the offset of the slots that was noted prior to removal of the breakstuds from the GTC (refer to Figure 3).

The most important metallurgical conclusion, in terms of assessing the subject failure, is that 4 of the 8 breakstuds *failed due to fatigue cracks that initiated at grinding marks in the radius area.* The radii at each end of the reduced section is small, 1/32 inch (32 mils) nominal. Measurements by BEAR indicates that the actual radii dimension varies considerably due to the grinding manufacturing method of producing the reduced section. The minimum radius in the exemplar breakstuds examined was approximately 10 mils (thousandths of an inch), with the majority in the 22-30 mil range. The small dimension of the radii significantly increases the peak stresses in the breakstuds, as discussed in the next section of this report (see also Reference [4]).


Figure 14a and 14b. Breakstud #3 fractured through the radius at the end of the reduced section.

Breakstud #3 is shown in Figure14. Note the visible grinding scratches (Figure 14a) and the flat fatigue fracture surface and ratchet marks (initiation sites) from the 1 to 4 o'clock position. Surface grind marks in the fatigue damaged breakstuds are on the order of 60-80 micro-inches (millionths of an inch). Grind marks this deep can significantly reduce the fatigue strength of titanium alloys. Data presented in Reference [5] indicates that a surface roughness of this magnitude can decrease the fatigue strength of titanium alloys by more than a factor of 4. Most fatigue critical locations in titanium aircraft components are shot peened for this reason. The combination of high local stresses due to a small radius, a rough grinding process and a scratch sensitive material results in a very fatigue sensitive surface as shown in Figure 15.



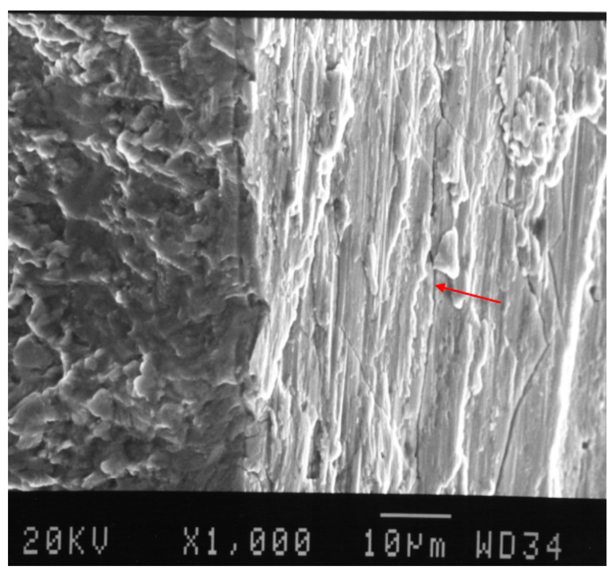


Figure 15a and 15b. Smeared metal on breakstud #1 reduced section surface from grinding (left). Grinding marks and secondary cracks (red arrow) on breakstud #3 surface (right).

Sectioning breakstuds #8 and #2 reveals a work-hardened surface layer due to the grinding manufacturing process as shown in Figures 16 and 17 below.

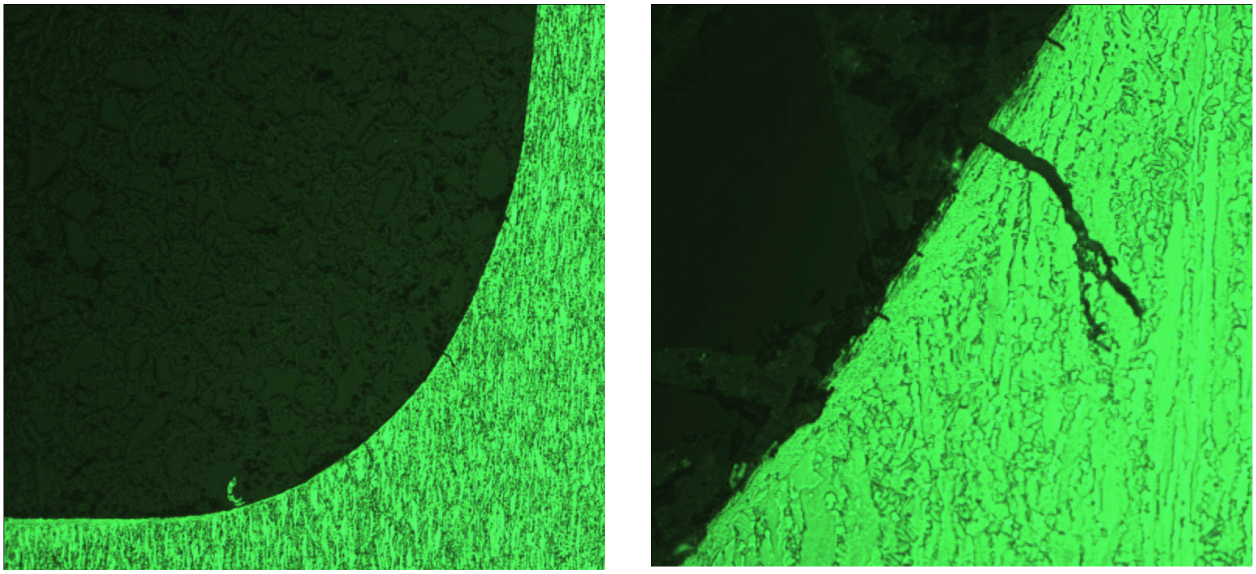


Figure 16a and 16b. Cracks in #8 breakstud radii that did not fracture through. Magnification is 50x on the left and 500x on the right. Note, the work hardened layer with numerous cracks.

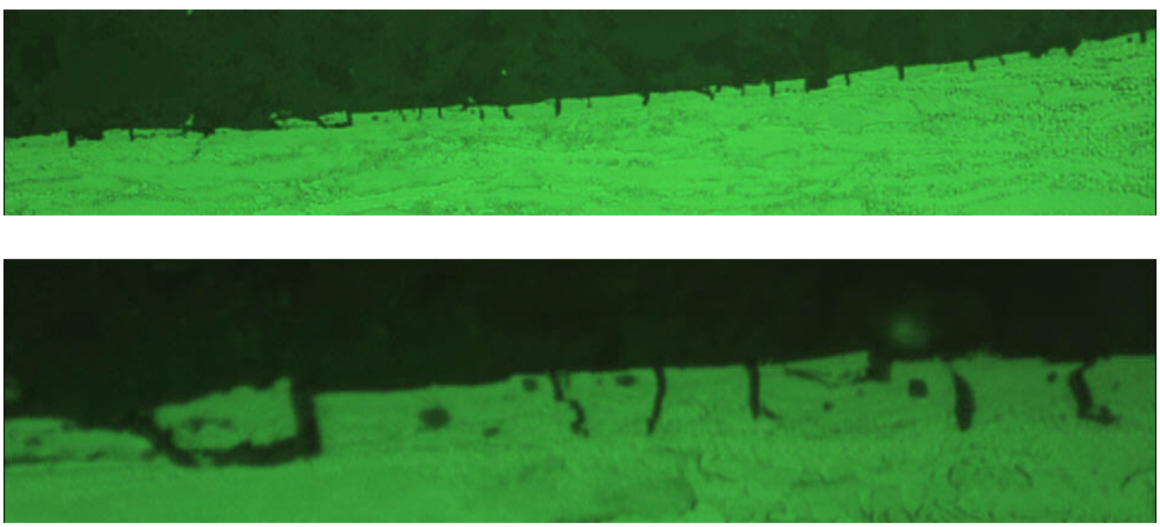


Figure 17a and 17b. Cracks in #2 breakstud reduced section. Magnification is 200x on the left and 1000x on the right. Note, the work hardened layer with numerous cracks. Breakstud #2 failed by overload.

5.0 Mechanical Analysis

Inspection of the bolts indicates fatigue crack initiation and growth on 4 of the 8 breakstuds: #1, #3, #4 and #8. The fatigue cracking occurred in the reduced section radii area [3]. In order to assess the cause of failure, a fatigue analysis was performed considering wave and operational loading.

5.1 Fatigue Analysis

A standard methodology for performing a fatigue analysis of a bolted joint is given in numerous texts on Mechanical Engineering Design [6-11]. Typically, a fatigue damage curve is determined for the subject component material, condition and operating environment.

In this case the material is a titanium alloy, Ti -4Al-6V. The surface condition is abusively ground for this material, particularly at transition locations in the reduced section radii (points where the radius changes and stresses are high). A fatigue endurance limit for this condition is 13 ksi as shown in Figure 18 [5]. The fatigue endurance limit is the stress level below which no fatigue damage occurs for no mean stress or preload.

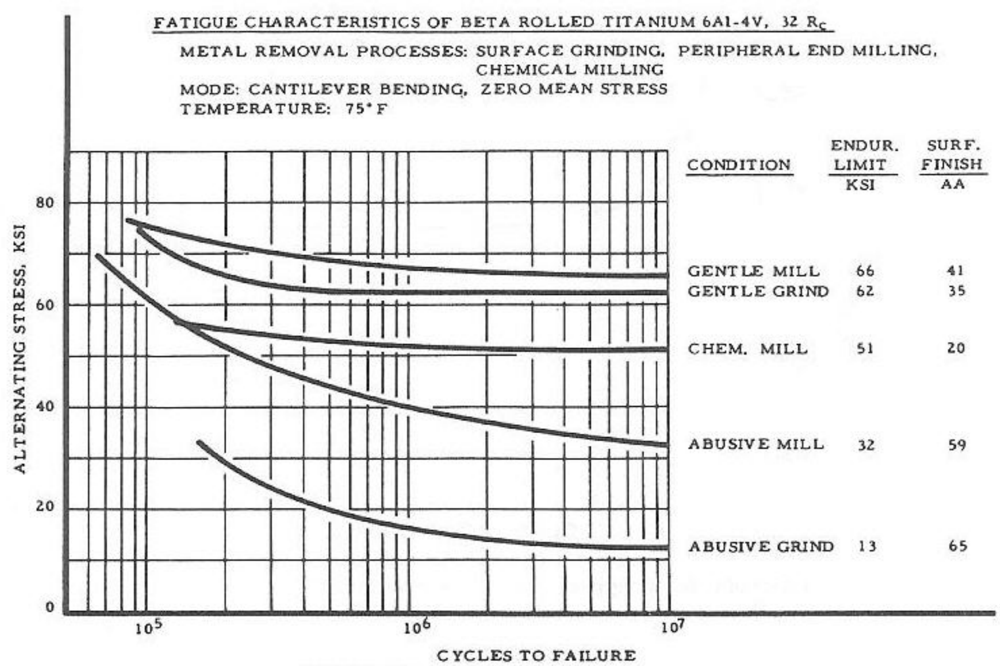


Figure 18. Fatigue characteristics of titanium alloy Ti-6Al-4V [11].

The Goodman Equation is used to adjust for mean stress and any stress concentrations, such as the radius at each end of the reduced section [6]:

$$Se = \frac{Sf}{SCF}\left(1 - \frac{Sm}{Su}\right) \qquad (1)$$

where *Se* is the adjusted failure stress at 10^7 cycles in the fatigue damage curve, *Sf* is the unadjusted fatigue stress, *Su* is the material ultimate stress, *Sm* the preload stress, and *SCF* is the local stress concentration factor.

The Morrow-model failure line was used in the prior assessment [4] instead of the Goodman Equation. This method can be very nonconservative for surface distressed materials, is only suggested in 1 of the 6 mechanical design text books referenced in this report [11], and then only with caveats about applicability and experience with steels and aluminum.

The radius at each end of the reduced section causes a local stress increase that can be characterized by a stress concentration factor (SCF). The SCF is a multiplicative factor; the nominal stress in the reduced section multiplied by the SCF gives the peak local stress in the radius. They can be calculated using formulas given in Reference [12]. For the minimum radius, 10 mils, found in the exemplar breakstuds, the SCF is approximately 3.0 as shown in Figure 19. The local peak stress in the radius is approximately 3 x higher than the nominal stress in the reduced section.

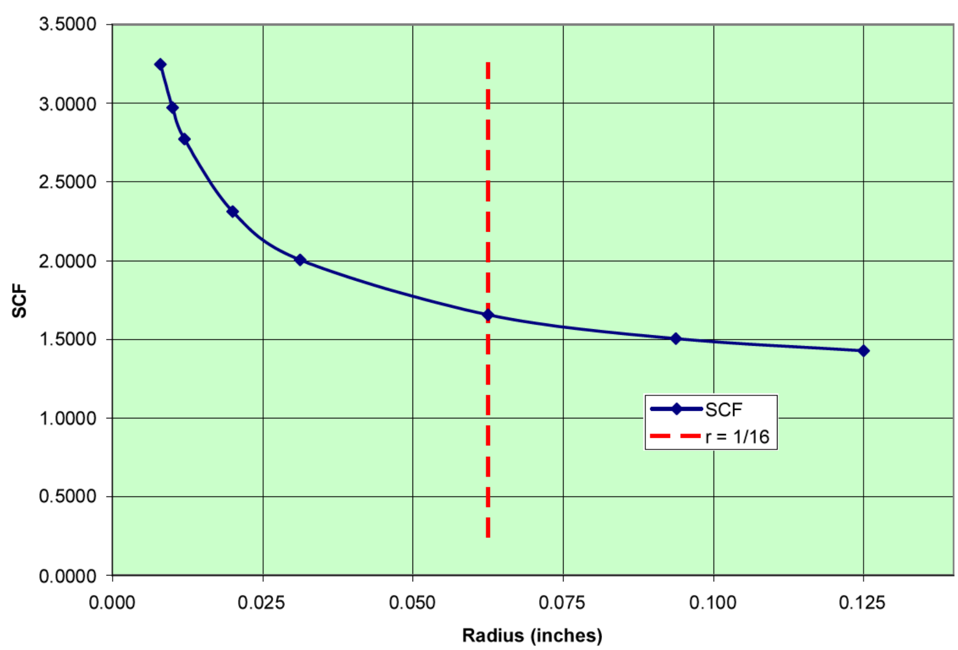


Figure 19. SCF as a function of radius dimension in the breakstud reduced section.

Note, that requiring all radii to be no less than 1/16 inches reduces the peak stress by almost a factor of 2, relative to the minimum measured radii. Plotting the same results on the SCF design graph shown in Figure 20, indicates that the subject SCF range for the current breakstud (drawn in dashed line) is above and to the right of the given published design data (solid lines); this should serve as a red flag to any designer.

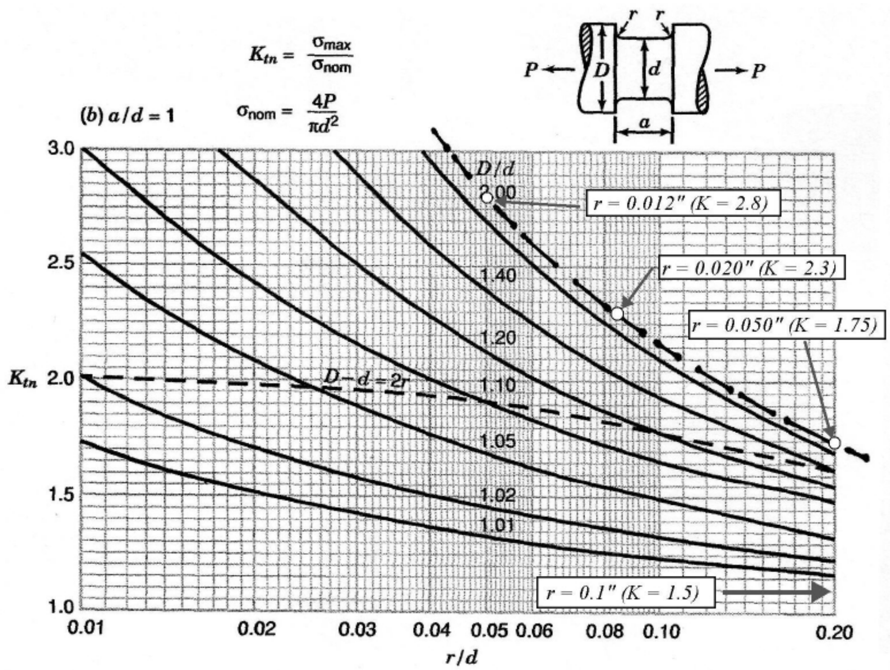


Figure 20. SCF data for the breakstud plotted against design data [13].

With a range of possible SCFs, the right end of a damage fatigue curve, *Se*, is determined with Equation 1 at 10^7 cycles. For a SCF of 3.0, Sf is approximately equal to 1.3 ksi. The left end of a fatigue damage curve is typically defined as 90% of the ultimate stress, *Su*, at 10^3 cycles to fail [5]:

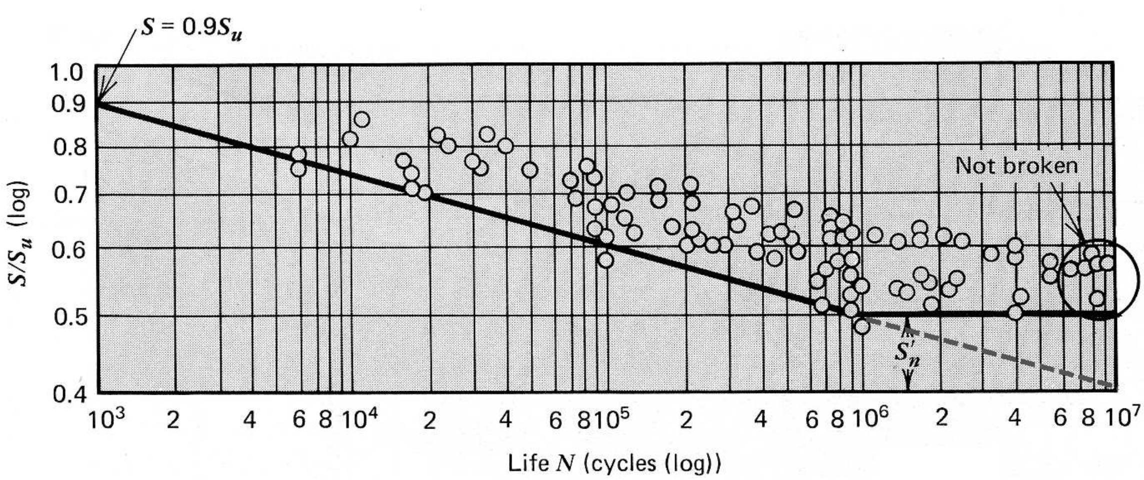


Figure 21. Conceptual fatigue curve [8]. The dashed line represents no endurance limit.

With two points of the fatigue curve defined, the fatigue or S-N curve (stress, number of cycles to failure) can be expressed by a linear function in log-log space:

$$N\,S^{m} = A \qquad (2)$$

where S is the applied cyclic stress (amplitude), N is the cycles to failure and A and m are equation constants determined from the two points discussed previously. Fatigue damage, D, is defined by Miner's Rule:

$$D = \sum_{i} \frac{n_i}{N_i} \qquad (3)$$

where n_i is the number of cycles at a particular stress level, and N_i is the number of cycles to fail at a particular stress level defined by Equation 2. Failure is assumed to occur when $D = 1$. Assuming the cyclic loading forces are available in blocks continuous spectra (e.g. spectral wave density data), and utilizing Equations 2 and 3, incremental damage for any cyclic stress level, σ_i, and n number of cycles at that stress level, can be expressed as:

$$D_i = \frac{n_i\,\beta}{A}\left(\sqrt{2}\,\sigma_i\right)^{m} \qquad (4)$$

where β is the rainflow correction factor [14] to account for the fact that waves characterized by frequency domain data do not interfere with each other as they would in the time domain; it is a reduction factor approximately equal to 0.85. Cyclic stress can be expressed as a function of wave height [15]:

$$\sigma(H) = \frac{7}{36}\frac{C\,Do\,\rho w}{Z\;Abolt\;\tau^{2}}\,\lambda(H)\,(H)^{2} \qquad (5)$$

where H is wave height, Do is the hose string outside diameter, τ is the corresponding wave period, $Abolt$ is the cross sectional area of the breakstud reduced section, Z is the cross sectional moment of inertia of the breakstuds, ρw is the density of sea water, and C is the fraction of cyclic load experienced by the breakstud [5]:

$$C = \frac{Kb}{Kb + Km}; \qquad Kb = 1/\sum\frac{1}{kb} \qquad \textit{and} \qquad kb = \frac{A\,E}{L} \qquad (6)$$

where Kb is the stiffness of the bolt, kb an individual component of the bolt (e.g. the reduced section), and Km is the stiffness of the flange (members being bolted together). Note that breakstud stiffness is inversely proportional to length. Thus, the longer the reduced section in the breakstud, the less cyclic load it will experience (C is lower). The flange stiffness was calculated with similar equations given in References [5-11] and verified with the finite element model.

With equations 4, 5 and 6 and the spectral wave data offshore of Hawaii, life can be estimated for the failed GTC as a function of SCF:

Radius (in)	SCF	Life (yrs)
1/16	1.6	5.2
1/32	2.0	2.9
1/64	2.5	1.7
1/100	3.0	1.2

The subject GTC released in approximately 2.75 years, indicating a radius slightly less than specified (1/32 inches or 33 mils), which is consistent with the exemplar measured values, most ranging between 25 and 30 mils.

In addition to the wave loading, 400 cycles per year of 20 kip load applications were assumed to account for testing, towing to/from ships at the SPM and the multiple pressures cycles that occur during product transfer. This loading has little effect on life due to the low number of cycles. No endurance limit was assumed for the calculation results given above because of the significant plastic deformation in the reduced section radii and surface trauma due to the manufacturing grinding process. This is consistent with fatigue assessments of components experiencing surface distress (e.g. stainless steel in a stress corrosion cracking environment, carbon steel in salt water corrosion, sand cast materials, and in this case titanium with a work hardened and scratched surface exposed to stresses above yield).

Rerunning the same life assessment with a modified design (stress concentration of 1.0), a minimum surface finish of 16 AA and a reduced section length of 5/8 inches) results in an infinite life if the breakstud torque is maintained and a 7 year life for a complete loss of torque. An endurance limit is now taken into account.

A stress concentration of approximately 1.0 can be obtained using an exponentially shaped radius profile at each end of the reduced section profile [13]:

$$\frac{d}{do} = 0.0043 \exp(3.62\, x / do) \quad (7)$$

where *do* is the nominal diameter of the reduced section, *d* is diameter as a function of *x* inches through the profiled radius at each end of the reduced section. The distance *x* is assumed to start (location of $x = 0$) 2 diameters from the wall at each end of the reduced section. Equation 7 is a curve fit to the tabular data given in Reference [13] and would require increasing the length of the reduced section 3 times, from 5/16 inches to 15/16 inches. Similar profiles could easily be developed for shorter reduced sections. Gall Thomson has moved to a CNC machining method and away from grinding to produce the reduced section. Thus, implementing a radius profile represented by an equation is fairly straight forward. The length of the reduced section can be increased in the GTC without significant modification. The length of threaded engagement corresponds to that required for a 5/8 inch stud, not that required for a 1/4 inch reduced section. The threaded section can be shortened with out compromising the design.

5.2 Preload

The preload for the breakstuds is specified at 5150 lbs ± 250 lbs, 75% of the ultimate strength. The preload has historically been obtained by torquing each breakstud to 90 ft-lbs. Preload forces have been shown to vary significantly with torque in the literature [6] and by strain gage measurement in GTC breakstuds [4]. For this reason, FaAA recommended strain gages be installed in the breakstuds to more accurately set the preload. This recommendation had been implemented in the subject GTC.

While strain gages can be very accurate, they also can be a distraction from performing the basics correctly (e.g. tracking torque, nut and stud rotation). The current preload procedure is 13 pages long and involves spreadsheet calculations, the calibration and tracking of electronic instrumentation, as well as the physical action of torquing the breakstuds (see Appendix A, “Breakstud Preload Procedure”).

Given the potential preload problems of over/under torquing, the best course of action is a simple method which includes the tracking of breakstud and nut rotation. Furthermore, it would be beneficial to improve the breakstud design so that it will function properly with a wide variance in preload. Adding a crowfoot extension to the torque wrench will allow observation of the nut and breakstud during torquing.

The currently specified preload of 5150 lbs is adequate for both hydraulic tensioning and torque methods monitored with strain gages. For preload with a torque wrench only, the existing torque specification, 90 ft-lbs, is also adequate as the actual preload is 25% to 30% lower than the specified 5150 lbs and more centrally located in terms of preload margin both high and low.

6.0 Discussion

The fatigue analysis in the last section clearly indicates that the combination of a high stress concentration, distressed surface conditions and high preload can cause a GTC to fail prematurely in operation. Other contributing factors are always possible, but are unlikely in this case. Partial necking and fatigue on 4 breakstuds #1, #3, #4 and #8 which are not sequential (not adjacent to each other) indicates excessive preload and fatigue failure of the breakstuds. The non-sequential fatigue damage indicates the loading mechanism is bolt-specific. Necking without failing in the necked area indicates a displacement-limited loading mechanism; that is the load must stall in terms of displacement just after the peak load occurs (onset of necking), but before failure. Only rotation of the breakstud nuts is capable of such displacement control. In addition, scrape marks on some of the breakstuds indicates they were rotated past their anti-rotation pins.

The new preload procedure relying on electronic strain gages exposes the anti-rotation pins to as much as 60% more torque. It is not clear that they are reliable at this higher torque. Electronic strain gages can be very accurate, but are often unreliable. The new procedure is quite complicated, requiring spreadsheet calculations and the calibration and tracking of electronic instruments in addition to the physical action of torquing the breakstuds. Any errors in this procedure risks exposing the breakstuds to excessive preload and a significantly shorter life. This does not mean the high preload is the primary cause. The poor design of the breakstuds, makes them particularly sensitive to both high and low preloads.

The breakstud design details are contrary to standard textbook recommendations for reducing the likelihood of fatigue in bolted connections: (i) the small radii at each end of the reduced section increases stresses by as much as a factor of 3; (ii) the relatively rough and work hardened reduced section surface finish can decrease the titanium material fatigue strength by as much as a factor of 5; and (iii) the short length of the reduced section unnecessarily increases the portion of cyclic wave loading passing through the breakstuds instead of the flange, results in little elastic stretch at the design preload and produces large variations in preload for small differences in applied torque and nut rotation.

The GTC design has never been subjected to a rigorous fitness for service review. The manufacturer, Gall Thomson, has never performed a stress/fatigue analysis appropriate for the subject service, nor a risk assessment indicating this device actually lowers the risk of a spill. Gall Thomson, has stated in correspondence that the GTC is "*immune from fatigue*" as long as the breakstuds are properly preloaded [17]. This is simply incorrect. FaAA, in their analysis and redesign of the breakstuds, correctly concluded that the stresses are extremely high at the small radii and "*the primary source of cyclic loading on the GTC in service is wave induced bending*". They did not, however, perform a fatigue analysis considering the defective breakstud design details or recommend improvements.

The recommendation to install strain gages resulted in an increased preload which aggravated the stud design deficiencies and may have distracted the installers from more important tightening fundamentals (e.g. tracking torque, nut and stud rotation).

BEAR also provided assistance, working with Gall Thomson, FaAA and Tesoro Hawaii, in specifying upgraded bolts for the changeout this September. The changes agreed to by all parties (Gall Thomson, FaAA and Tesoro Hawaii) are given in BEAR drawing 06-2447G-1. The reduced section radii are increased from 1/32 inches nominal to 1/16 inches minimum and the surface roughness is to be 16 AA (micro-inches) or better. These changes have resulted in Gall Thomson moving from grinding to a computerized numerical controlled (CNC) machining method of forming the reduced section. With a CNC method of manufacture, the stress concentration factor at the reduced section radii can probably be reduced to near 1.0 by using an exponentially shaped profile. With a few small changes, the breakstud life can be increased to near infinite with a tolerance for a wide variance in preload.

That is of course, if the GTC makes it into the water without any significant damage. The GTC is heavy and must be lifted, transported and installed to a floating condition in the ocean using cranes or other heavy lift devices. In addition, what is normal grinding and machining for most materials, is “abusive” for titanium alloys. Removing too much material too fast results in a cracked and work hardened surface with little fatigue resistance. Many aircraft component manufacturers either shot peen the surface in fatigue-critical areas or polish off a layer at least half the thickness of the last metal removal process. This is a high technology device that has clearly not been subject to a thorough “Fitness for Service” evaluation as evidenced by the approximately 160 releases experienced by roughly 1000 in service Gall Thomson GTCs. The most appropriate remedy may be to remove the GTC devices from service. As discussed in the background section and Reference [1], numerous safety measures have been implemented to make a spill caused by a ship at the SPM becoming unmoored a very unlikely event:

1) Load monitoring of the hawser (main ship mooring line to the buoy system).

2) 24 hours/day low light TV/infrared surveillance of the SPM.

3) Transfer of two qualified Mooring Masters to the ship while at the terminal.

4) Requiring the ship to maintain live watches at the bow and transfer manifold.

5) A 4,000 hp tug tethered astern of any moored vessel at all times while at the SPM.

It is not clear that the presence of even a well designed GTC lowers the risk of a spill [18]. There are several quick release devices on the market with excellent field experience (e.g. the Quikcon by FMC Energy Systems). The Quikcon coupling is currently being used at Tesoro's Alaska wharf with good success and no accidental releases. These devices have the added advantages of attaching to any common style flange (Metric, ANSI and BS), not requiring bolt hole alignment, and having a built in gasket as well as being easily releaseable with a standard wrench/spanner. These devices would meet the intent of the Coast Guard recommendation to *“provide the means of rapid cargo hose removal”* without the risk of accidental releases. Relying on a quick release device will require personnel stationed at the manifold to be in communication with the ship’s pilot, and/or others, and to have any required tools and parts on hand and in good working order.

7.0 Conclusions and Recommendations

The analysis clearly indicates the GTC release resulted from the combination of three causes:

1) A new breakstud preload procedure. The new procedure produces higher preloads which in combination with Cause (2) is detrimental to fatigue life. The new procedure also relies on electronic strain gages to determine preload, which can be a distraction from assembly fundamentals (e.g. tracking breakstud and nut rotation).

2) A breakstud design that is highly susceptible to fatigue. The Gall Thomson breakstud design details are contrary to standard textbook recommendations for reducing the likelihood of fatigue in bolted connections: (i) small radii at the highest stress location; (ii) a relatively rough ground and work hardened surface finish; and (iii) a short effective stud length.

3) Lack of a proper "Fitness For Service" evaluation. The manufacturer has never performed a stress/fatigue analysis appropriate for the subject service, nor a risk assessment indicating this device actually lowers the risk of a spill.

To reduce the risk of an inadvertent release, Tesoro should consider the following short term recommendations:

1) A bolt-up procedure with more checks and balances (e.g. tracking applied torque, nut rotation, and stud rotation).

2) A more robust breakstud design as described in the Mechanical Design section of this report and as currently being implemented for the upcoming changeout in September, 2006.

For the long term, Tesoro should consider removing the connectors from the SPM hose system. The devices are by design a weak link and will always retain some risk due to manufacture, handling, installation, and/or abuse in operation. Assuming Tesoro continues to use the connectors, BEAR additionally recommends the following breakstud improvements:

3) A large exponentially shaped radius transition as described in Section 5.1 of this report, to further reduce stresses in the radii and make the radii surface finish more inspectible.

4) Increasing the length of the reduced area section.

5) Hydraulic stud preloading.

6) Strongly consider eliminating the strain gages.

8.0 References

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