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OPTIMIZATION OF RE-TORQUE AND RELAXATION PARAMETERS OF THE GUCP

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ABSTRACT

Self-loosening of bolts in non-permanent connections has been the subject of a myriad of investigations; however, because the vast majority of these studies focused on applications with long-term service conditions involving creep and/or cyclic (working or vibratory) loading, there are no analytical techniques that have been developed to address the load decay behavior of bolted assemblies with gaskets under a primary followed up by a secondary torque. The Ground Umbilical Carrier Plate (GUCP) includes a gasketed ASME-type flange assembly that transfers pressurized, cryogenic hydrogen from the Space Transportation System (STS). Although the threaded stud material is nominally elastic under service conditions, the gasket material, a polytetrafluorethylene (PTFE) matrix filled with 25% chopped glass fibers, undergoes viscous, strain hardening deformation. The consequence of over-torquing the assembly is yielding the stud. Alternatively, the consequence of under-torquing is premature loosening and subsequent fuel leakage. As such, identifying the interactions between assembly configuration, initial torque, etc. to relaxation behavior of the assembly has been identified as a means to reduce the dwell period (the time between initial torque and re-torque). Research is carried out to identify the optimal torque parameters that confer a minimal dwell period. This article documents the Gasket Relaxation and Re-Torque Optimization (GRRO) program used to modify procedures employed when connecting the flanges to the fuel tank of the Space Transportation System prior to a launch.

1. NOMENCLATURE

δ Deflection [in or mm]
A Cross-sectional area [in^2 or mm^2]
C   Viscosity [lb/in/s or N/mm/s]
C_N Nut factor [unitless]

d Diameter of the stud [in or mm]
E Elastic modulus [ksi or MPa]
F Load [lb on N]
I Moment of inertia [in^4 or mm^4]
K Spring stiffness [lb/in or N/m]
L Length of stud grip [in or mm]
T_0 Initial torque [in-lb or N-m]
T_R Re-torque [in-lb or N-m]
t Time [hr]
t_0 Initial dwell period [hr]
t_G Gasket thickness [in or mm]

2. INTRODUCTION

During the initial launch countdown of STS-119, a hydrogen leak was detected and the launch was scrubbed until repairs could be made. The repair required removal and replacement (R&R) of the Pad A External Tank (ET) Gaseous Hydrogen (GH2) Vent interface Quick Disconnect (QD) and, subsequently, the de-mate of the ET GH2 vent line 4 *ft* (1.22 *m*) flexhose forward flange from the QD flange, shown in Fig. 1. Removal and reinstallation of the Ground Umbilical Carrier Plate (GUCP) disconnect required replacement of a polytetrafluorethylene (PTFE)-based gasket, torquing of the gasket flange, and a re-torque of the flange after a 30 *hr* dwell period per legacy specification. It was hypothesized that the re-torque parameters of such joints can be optimized and, as such, significant operational value may be realized.

It has been widely accepted that the phenomenon of time-dependent loosening of flange connections is a strong consequence of the viscous nature of the compression seal material. Characterizing the coupled interaction between gasket creep and elastic bolt stiffness has been useful in predicting conditions that facilitate leakage. Prior advances on this sub-class of bolted joints has led to the development of (1)

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Figure 1: Flexhose assembly of ground umbilical carrier plate (GUCP) with and (inset) without weather-resistant shroud.

constitutive models for viscoelastics, (2) modified tightening strategies, (3) gasket characterization test standards, and (4) development of advanced gasket materials (e.g. shape memory materials and heterogeneous materials). The effect of re-torque, which is a major consideration for the Shuttle System GUCP, has rarely been investigated, however.

Research was carried out to (1) investigate the main effects and interactions of multiple parameters on bolted joint load decay, and (2) develop an optimized re-torque process for the hyper- and cryo-system bolted joints. A brief review of the prior research related to the study is provided based on several areas. Concepts from literature relevant to the concepts applied in this study are included.

3. MECHANICS OF FLANGES AND RE-TORQUE

There have been many advances in the study of time-dependence of bolted connections since Smoley and his analysis of creep behavior (1968). In this section, we review concepts related to bolt tension decay. A bolt-flange-gasket system is a simple assembly involving three main components: multiple identical bolts, a gasket of uniform thickness, and mating flanges. Generally, this particular assembly can be modeled as a spring-mass-dampener system. The kinetics of each component is derived from equilibrium assumptions, free body diagrams of component geometries, and simplistic mechanical models. The spring coefficient (or spring stiffness) of the bolt, K_b, has been expressed in several forms, i.e.,

$$K_b = \begin{cases} \dfrac{\pi d^2 E_b}{4L} & [1] \\ \dfrac{E_b A_b}{I_b} & [2] \end{cases} \tag{1}$$

where d is the diameter, E_b is the Young's modulus, L is the length of the bolt or grip length (measured between the head and the nut), A_b is the cross-sectional area, and I_b is the moment of inertia. By design, the bolt material is not loaded to cause a plastic deformation of the bolt or flange. Equation (1), therefore, remains valid for most situations.

The spring element of the bolt is loaded in parallel with that of the joint (or flange), K_f, and gasket, K_g, which are applied in series. The former is expressed using the following [3]:

$$K_f = \frac{EA_c}{t} \tag{2}$$

where E is the modulus of elasticity of the flange material, A_c is an equivalent cross-sectional area of the joint, and t is the total thickness of the joint or grip length. The term K_f can be determined from the stress-deflection relationship of the system with the gasket removed.

Bickford [4] stated that gaskets must be able to flow to mate with the flange surfaces. The ideal gasket will behave elastically and exhibit recovery to accommodate physical and thermomechanical variations in the assembly over its operational life. This allows the gasket to mate with the flange surface and seal cracks through which liquids or gases might
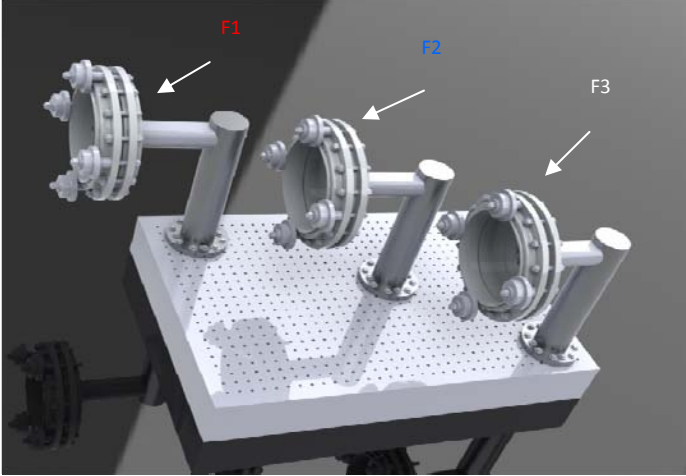
Figure 2: *Isometric view of rendition of the UCF/USA-designed gasketed flange test bed.*

otherwise escape. Polymeric gaskets, however, demonstrate viscoelastic behavior and thus are limited in life due to creep relaxation. Nassar and Alkelani [5] created an experiment to measure the relationship between the thickness of the gasket and gasket deflection. Even though gasket relaxation is affected by gasket thickness, t_G, a thicker gasket does not necessarily translate to increased relaxation. A thicker gasket allows for more time for the gasket to relax while it is being tightened.

The stiffness of the gasket is, therefore, the most complex of the stiffness parameters since (1) the material undergoes viscoelastic relaxation, (2) the material has strong temperature-dependence, and (3) gasket thickness and cross-sectional area have non-linear effects on performance. A Burger-type model for K_g is needed capture the time-dependence once the compressive force is applied and relaxation occurs. The equivalent gasket stiffness at any time t after compressing the gasket has been given by Alkelani and coworkers [6]:

$$K_g(t) = \left[\frac{K_1 + K_2}{K_1 K_2} + \frac{t}{C_1} - \frac{1}{K_2} \exp\left(-\frac{K_2 t}{C_2} \right) \right]^{-1} \quad (3)$$

This variable stiffness expression relates gasket force history to gasket deflection history. Constants presented in this model refer to elastic response (K_1, K_2) and viscous response (C_1, C_2) for a specific gasket. Each of these values can be determined experimentally on specimen-sized samples. Initially (at $t = 0$), the response of the gasket is solely determined by the elastic constant, K_1, only. At very long times, K_g reduces to zero. The remaining expressions, K_2, C_1, and C_2 determine the behavior in between. It is important to note that this relation is designed for a material subjected to continuous contact, single bolt connections. The stud (or bolt) and gasket stiffness may be combined to relate to load decay using the following [6]:

$$F(t) = \left[\delta_b(0) - \delta_g(0) \right] \left[\frac{K_b K_g(t)}{K_b - K_g(t)} \right] \quad (4)$$

Torque decay can be expressed using thread mechanics, i.e.,

$$T = C_N d F(t) \quad (5)$$

where the compressive load is measured by F in *lb* (or *N*); d is the nominal diameter of the bolt measured in units of *in* (or in *mm*); and C_N is a unitless nut factor that is specific to application (0.2 to 0.4 is common).

With the exception of studies by Waterland and Frew [7], the topic "re-torque" is scantily covered. Creep relaxation responses of various filled PTFE materials were compared based on the following performance metrics: stabilized slope after torque/re-torque and creep relaxation percentage after torque/re-torque. It was shown that ceramic-reinforced materials suffer more significant percent load loss compared to standard materials. A typical load/elongation loss after initial torque was 40%. Some non-reinforced materials required long dwell periods to establish favorable responses after re-torque. The most notable finding in their work is that some ceramic-reinforced materials are indifferent to dwell duration.

Mechanical properties of some gasket materials, such as PTFE-based materials, can be enhanced by adding fillers including glass fibers, carbon, graphite, molybdenum disulphide, and bronze. The matrix PTFE maintains excellent chemical and high temperature characteristics, while fillers improve mechanical strength, stability, and wear resistance. Fiberglass-reinforced gasket materials are desirable due to their low deformation at high stress, non-reactivity in very caustic environments, and stability at cryogenic temperatures. The volume fraction of fillers used to reinforce gaskets is too small to interfere with the flow process during initial loading, thus allowing the gasket material to form a good seal with flange surfaces. In the long term, however, the reinforcement acts as an obstacle that limits compressive deformation. Gasket reinforcement volume fraction is typically 25%, but 15% and 20% are also common.

4. EXPERIMENTAL APPROACH

An experimental program was carried out to determine the optimal re-torque parameters for the GUCP. Test parameters include gasket thickness (t_G), mating surface serrations (concentric), lubrication (fastener friction - with Krytox), initial clamping torque (T_0), re-torque or dwell time (t_0), and re-torque (T_R). Considerations of flange design per ASME B16.5 and gasket relaxation testing per ASTM F38 [8] were taken into account in the development of the test plan.

A test platform was designed and fabricated for mechanically characterizing the response of the GUCP, as shown in Fig. 2. The actual platform includes three exact replicas of the GUCP assembly including flanges, gasket, and studs. The platform was designed to allow three experiments to be conducted simultaneously. Each replica has 16 identical and equally-spaced studs; 25% of the studs were equipped with load cells and strain gages to measure the relaxation response of the bolted connection before, during and after the initial and
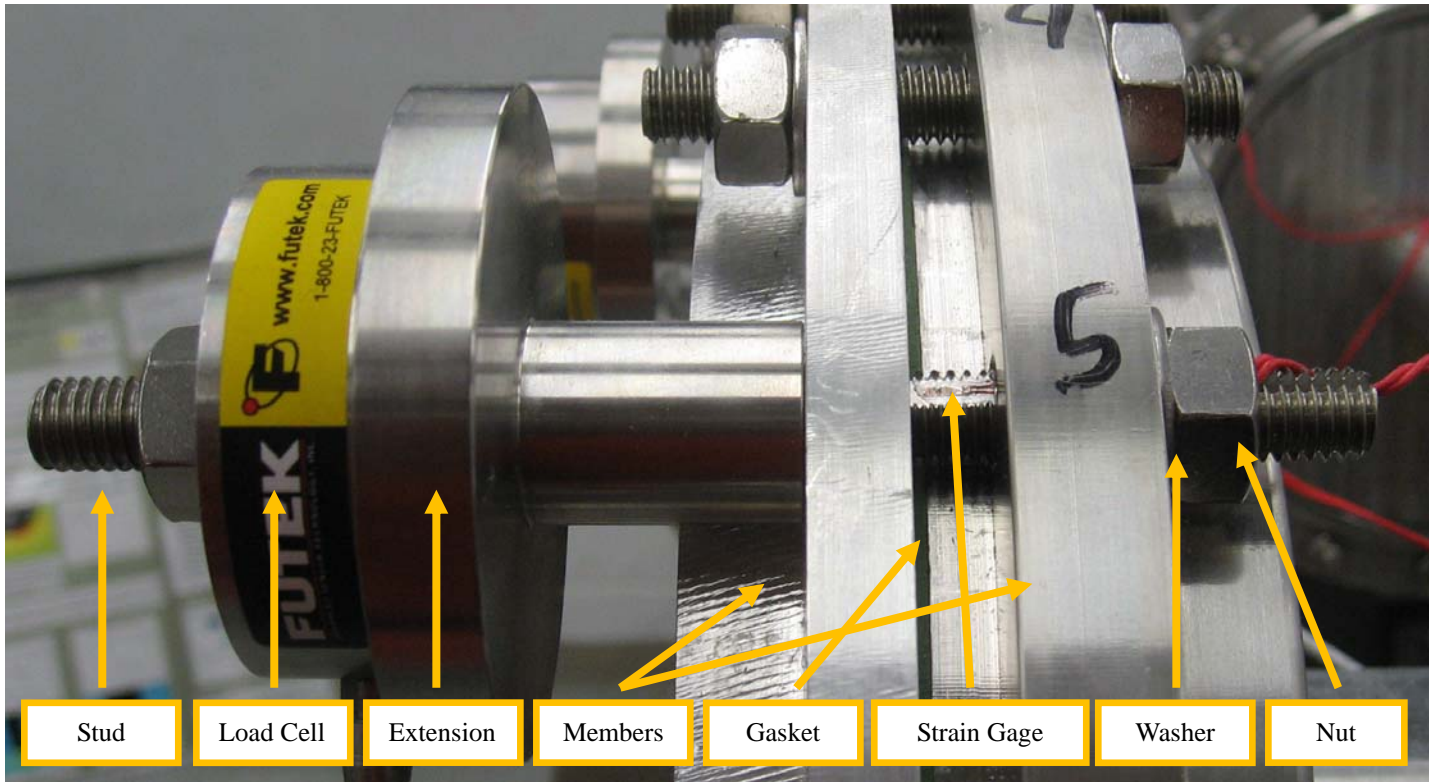
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| Stud | Load Cell | Extension | Members | Gasket | Strain Gage | Washer | Nut |

Figure 3: Flange assembly replica of the STS Ground Umbilical Carrier Plate (GUCP) designed and fabricated at UCF.
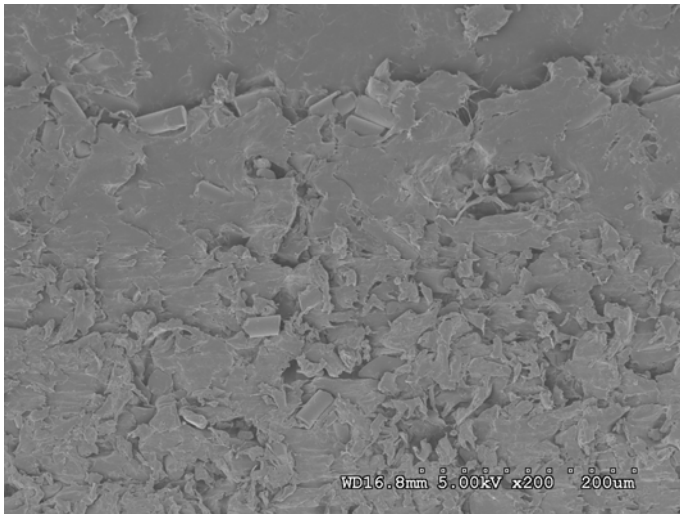

Figure 4: Scanning electron micrograph of a generic gasket material prior to application of mechanical loading.

final torques were applied. All sensors were connected to a data acquisition (DAQ) system that digitized the transduced signals to a computer. The computer was operated by way of a graphical user interface (GUI) developed in LabView to monitor the sensor signals and record data for these specific experiments. A fiberglass-reinforced PTFE gasket was used. The reinforcement takes the form of short, white glass fibers approximately 787 *μin* (20 *μm*) in diameter, but varying in length and having a volume fraction of approximately 25%, as shown in Fig. 3. The detailed configuration of a replica within the test platform is shown in Fig. 4.

It is known through available literature that gasket response is highly-dependent on history. Care was taken in the current study to ensure that the assembly and tightening procedures were not only consistent from experiment to experiment, but also done in accordance with standard practices associated with gasketed flange assemblies. Several tightening strategies have been studied by Nassar and Alkelani [5] (i.e., star, clockwise, and simultaneous). For the current study, bolts were initially hand-tightened. The star pattern was used to fully load the assembly: initial star [tightened up to 33% ± 10 *in-lb* (1.13 *N-m*) of final torque], second star (66% ± 10 *in-lb*), and final star (100% ± 2 *in-lb*). A digital torque wrench was used to ensure the desired torque was applied to the joint. When the wrench was released from the sixteenth bolt, clock time was set to zero and the dwell period commenced. The re-torque was applied in the identical manner as the final star. The benchmark initial torque that is applied in the actual service condition is 216 *in-lb* (24.4 *N-m*) nominal. Other benchmark parameters pertain to the lubricant (i.e., Krytox 240 AC), flange serration detail (i.e., concentrically serrated), gasket thickness [i.e., 0.09375 *in* (2.38 *mm*)], dwell period (i.e., 30 *hr*), and final torque (also referred to as re-torque) (i.e., 216 *in-lb* nominal). The values of the main test variables, as well as the rationale for their selection, used for the study (i.e., T_0, T_R, t_0, and t_G) will be described.

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The test program was separated into four distinct phases, numbered 1 through 4. Phase 1 was conducted to provide an indication of the variance in the gasket which could be expected over a number of trials and to serve as the benchmark. As a result of the initial evaluation, it was determined that three trials per experimental treatment combination would be required in order to obtain data, which would meet a standard of 95% confidence with an acceptable level of maximal error. This would result in only a 5% risk of falsely rejecting the null hypothesis given the various treatment combinations of the experiments conducted. Phase 2 experiments were designed to test for any differences in the relaxation response as a function of gasket thickness and initial torque. Phase 3 experiments applied the optimized gasket thickness and initial torque determined in Phase 2 and evaluated shortened initial dwell periods to re-torque. The final phase, Phase 4, of test program was designed to validate the results by comparing results acquired from both benchmark and optimized conditions.

5. INITIAL RESPONSE

Phase 1 of test program consisted of screening runs to provide an indication of the variance in the relaxation which could be expected over a number of trials. Test parameters were set to the benchmark conditions except a thicker-than-nominal gasket [0.125 *in* (3.18 *mm*)] was used since this was expected to provide the most significant relaxation response compared to thinner samples. Two sets of three experiments were conducted. The first set termed Sub-Phase 1.1, consisted of collecting data on each of the replicas. The four data curves corresponding to the instrumented studs for each of the replicas were treated independently. The variance was calculated for these twelve records at differing times after initial torque and after re-torque. Following the first set of runs, a second set (termed Sub-Phase 1.2) was conducted under the same conditions to add another twelve samples to the data set.

Comparing the load decay response of the first twelve to the second twelve was carried out to determine which of the possible consequences would arise. The calculation for the number of experiments required involved using an acceptable risk of inaccuracy, on this predicted population mean, of less than 5% and an acceptable level of error in the prediction of this mean.

Having estimated the number of runs required from Phase 1, Phase 2 of the test program was implemented. This consisted of a mix of between- and within-groups factors Analysis of Variance (ANOVA). The two between-groups factors consisted of gasket thickness and initial torque. Each of these factors had three levels. Gasket thickness was predetermined to have the following three levels, 0.0625 *in* (1.59 *mm*), 0.09375 *in* (2.38 *mm*), and 0.125 *in* (3.18 *mm*). Torque levels were 206, 216, and 226 *in-lb*. The three levels were selected such that the differences between the levels were of equal intervals between level one and two and between level two and three. The one within-groups factor consisted of the intervals of time (i.e., sampling frequency) across which the
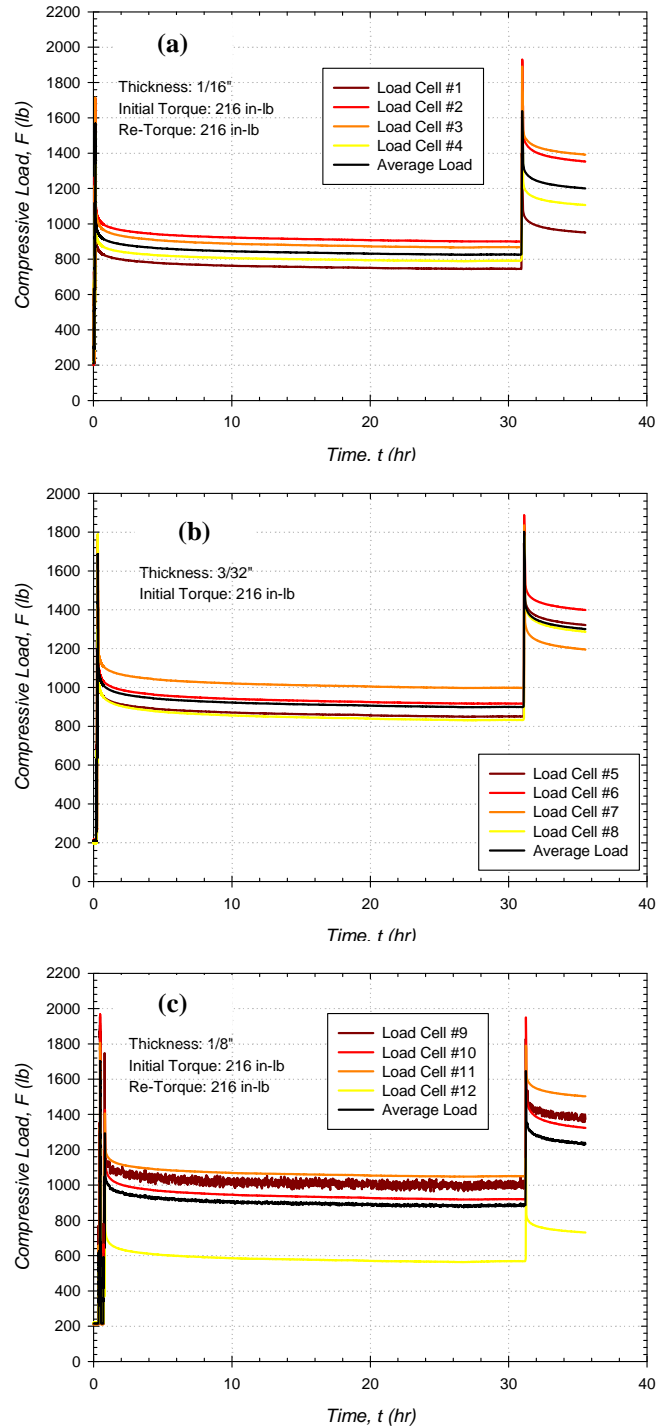

Figure 5: *Time-dependent response of (a) 0.0625 in, (b) 0.09375 in, and (c) 0.125 in gasket material under an equivalent initial and final torque.*

relaxation response was measured. The measure of relaxation was reduced to each of the three sampling rates for each run. Similar to gasket thickness and initial torque, the sampling frequency also had three levels, once (0.277 *mHz*), twice (0.555 *mHz*), and thrice (0.833 *mHz*) per hour. Because the sampling frequency was a
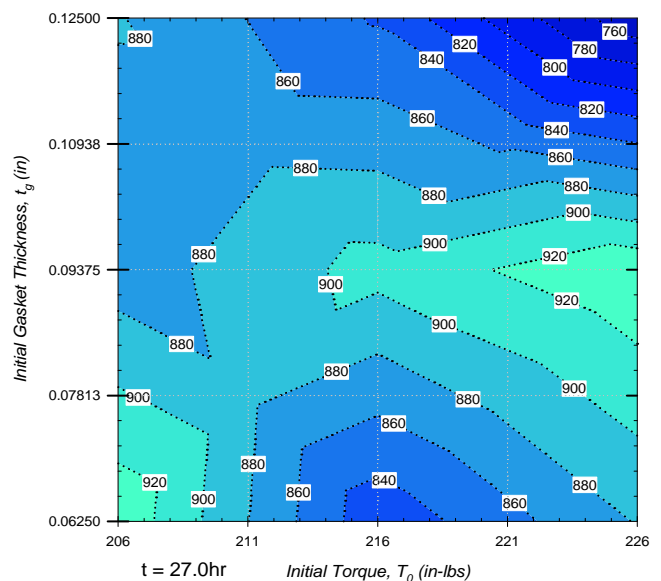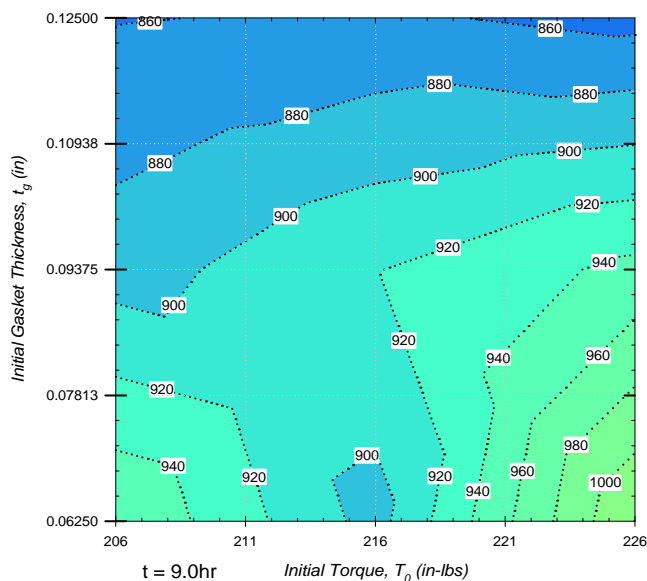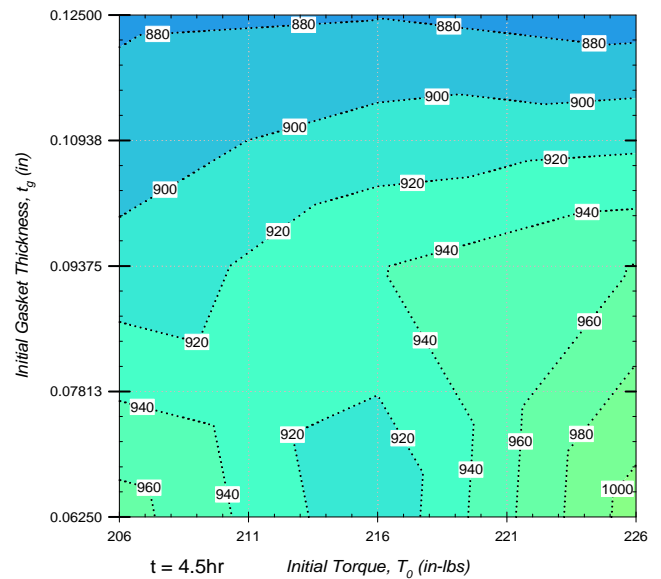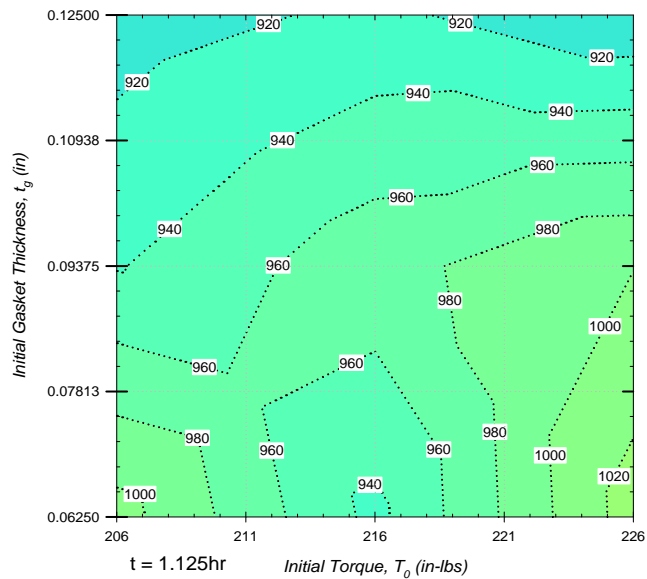
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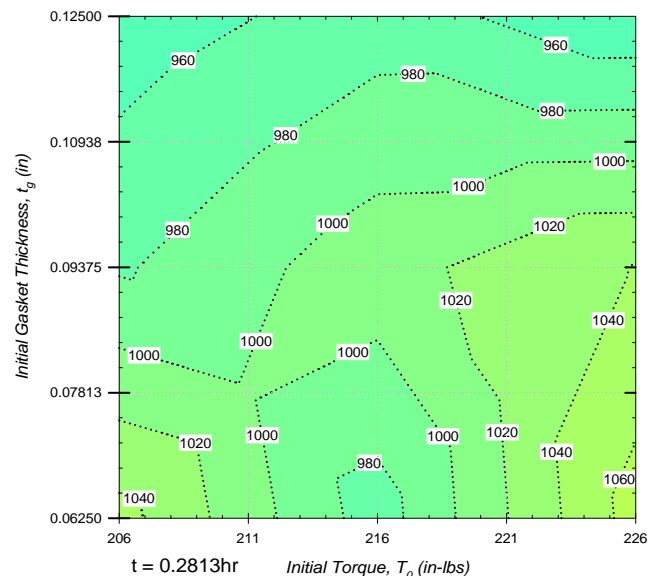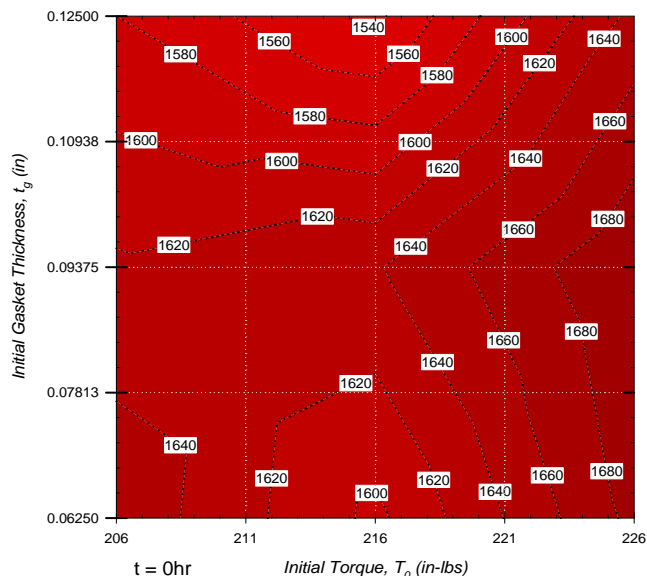
Figure 6: Experimentally-measured compressive load decay at various time steps.

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post-processing variable, only one experiment was needed per three sampling frequencies; therefore, while all 27 combinations of variables were analyzed, only nine unique combinations were conducted. A dwell period of 30 *hr* was applied to each. Data acquired from single experiments but multiple load cells were averaged and some are shown in Figs. 5a through 5c. Even though a re-torque equivalent to the initial torque was applied to each, only the dwell period was analyzed in Phase 2.

While Phase 1 revealed the variance of the experiments, Phase 2 allowed the significance of three parameters (or effects) to be characterized. All results from Phase 2 are shown as contours on Fig. 6. Each graph gives the decayed load after a given period of time. Various combinations of initial torque and gasket thickness between the nine tested couples are interpolated for each time slice. Based on the data, several observations were drawn. The most significant drop-off from the initial load at any combination occurs within the first hour of loading. For all of the cases studied, there is an average of 43.3% drop-off in load during the first 4.5 *hr*. For the second 4.5 *hr*, however, the load decay is 1.5%. Sample frequency was determined to be inconsequential. Initial torque of 226 *in-lb* (25.5 *N-m*) yielded the least load decay; the average load decay (after 9 *hr*) for all gasket thicknesses considered was 930 *lb* (4.14 *kN*). This value decreased to 899 *lb* (4.00 *kN*) and 919 (4.09 *kN*) for the 206 *in-lb* (23.27 *N-m*) and 216 *in-lb* (24.4 *N-m*) initial torques, respectively. Larger initial torques confer a more favorable load decay response than lower ones do. Of all of the combinations of initial torque and gasket thickness evaluated, the 0.0625 *in* (1.59 *mm*) gasket, when torqued to 216 *in-lb*. displayed the least amount of load decay and hence the best overall load retention. The 0.09375 *in* (2.38 *mm*) gasket torqued to 226 *in-lb* also displayed favorable load retention. The 0.125 *in* (3.18 *mm*) gasket torqued to 206 *in-lb* displayed the most significant load decay.

Equation (5) indicates that the initial response can be used to establish the nut factor C_N. Based on the results, the nut factor varies between 0.337 and 0.367 for this joint, and it has an average of 0.351.

6. RE-TORQUE RESPONSE

From the results of the Phase 2 experiments, the optimal value for minimizing the relaxation response as a function of gasket thickness and initial torque were selected and held fixed. These values were 0.0625 *in* (1.59 *mm*) and 226 *in-lb*. Similar to Phase 2, the experimental design of Phase 3 also had two between-groups and one within-groups factors. The two between-groups factors consisted of dwell period and re-torque. Three levels of dwell period were set to 4.5, 9, and 13.5 *hr*. Three levels of re-torque were set to 206, 216, and 226 *in-lb*. The within-groups factor consisted of three different levels of time after re-torque and was set at 4.5, 9, and 13.5 *hr*. As was the case in Phase 2, the time after re-torque was a post-processing variable therefore only one experiment (i.e., 13.5 *hr*) was needed per three levels; therefore, while all 27
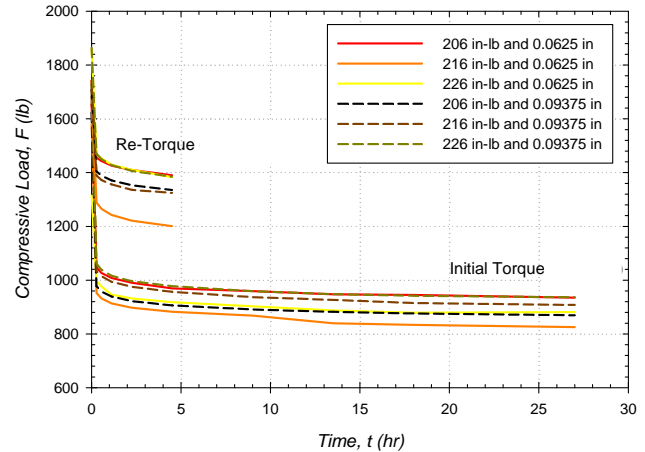

Figure 7: *Comparison of relaxation response before and after equal torque and re-torque.*

combinations of variables were analyzed, only nine unique combinations of were executed. Again three replicates were run for each of the nine combinations for a total of 27 runs. Different from Fig. 5, load decay upon re-torque is super-imposed with that captured from the dwell period for the purpose of comparison (Fig. 7).

Based on the analysis of the data, 226 *in-lb* of re-torque provides the most favorable response followed by 216 and 206 *in-lb*. The re-torque has a stronger influence on the load decay response and the dwell period has a comparatively weaker effect for the range of dwells considered. Of all factors and their interactions studied in Phase 3, only re-torque value and time after re-torque were found to be significant at a 95% confidence. There was no statistically significant difference among re-torquing at 4.5 *hr*, re-torquing at 9 *hr*, or re-torquing at 13.5 *hr*. As such, the conditions conferring the most favorable response are 226 *in-lb* in initial and re-torque, dwell period of 4.5 *hr*, and a gasket thickness of 0.0625 *in*. The re-torqued load decay response for this gasket thickness is shown in Fig. 8.

7. VALIDATION

The final phase (i.e., Phase 4) of test program was designed to validate the results by comparing results acquired from both benchmark and optimized conditions. Based on Phase 3 experimentation, the level of gasket thickness, initial torque, final torque, and dwell period resulting in the best performance was again selected. The load for this condition is shown in Fig. 9. The load decay of a gasket subjected to benchmark conditions is also shown. Figure 9 demonstrates that the 30 *hr* dwell period (legacy conditions) can be reduced to 4.5 *hr* when a thinner gasket is used with no loss of load carrying ability. Compared to the optimized configuration ($T_0 = T_R = 226$ *in-lb*, $t_0 = 4.5$ *hr*, and $t_G = 0.0625$ *in*), the decayed load based on the legacy torquing configuration (i.e., $T_0 = T_R = 216$ *in-lb*, $t_0 = 30$ *hr*, and $t_G = 0.09375$ *in*) after 4.5 *hr* of re-torque is nearly 100 *lb* (444.8 *N*) lower.
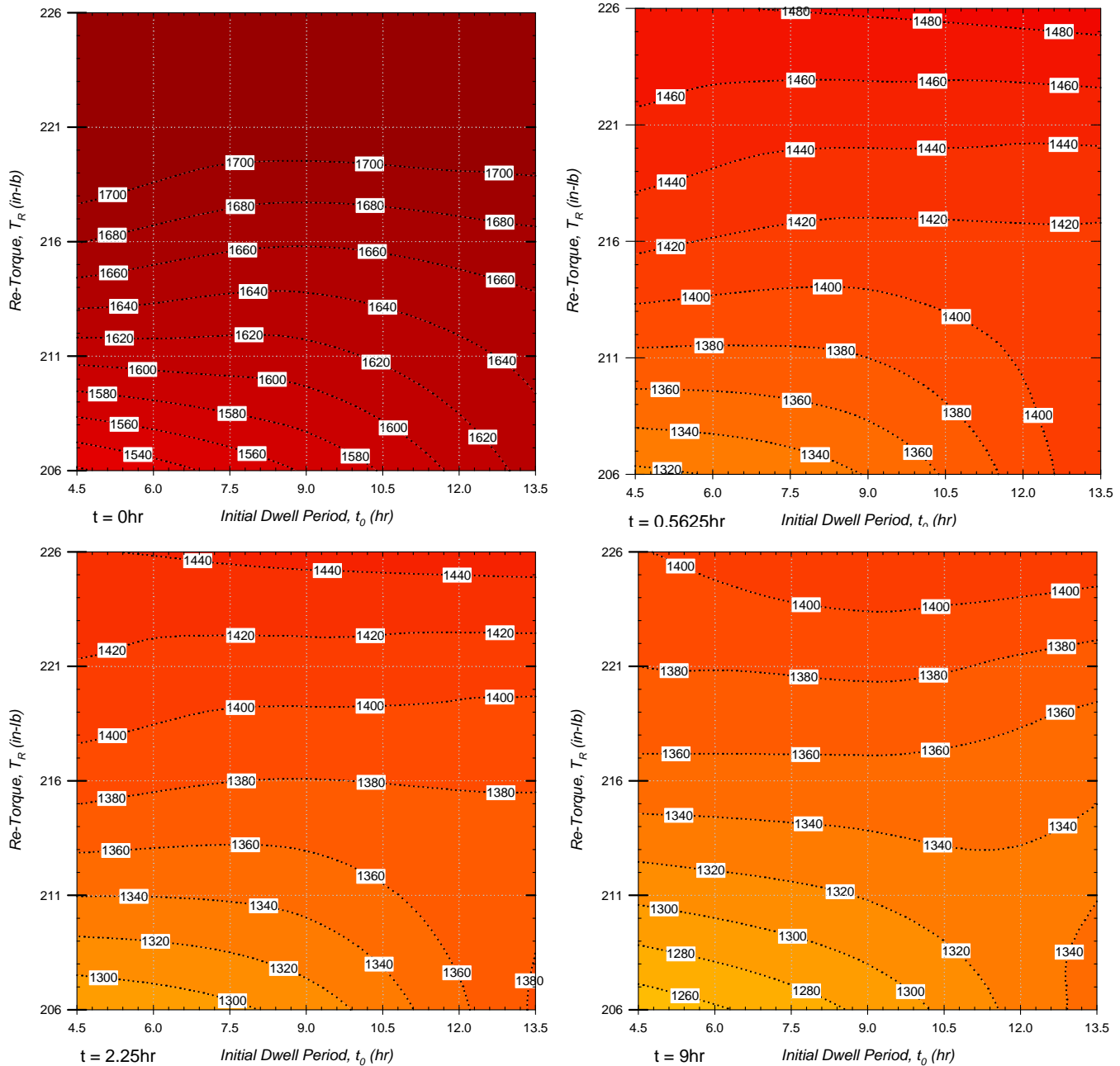
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Figure 8: Load decay of 0.0625 in gasket response after an initial torque of 226 in-lb, dwell period, and re-torque.

Tests at benchmark and optimal conditions were carried out three times each. The variances of these separate conditions are comparable. Results also show that the optimized torque procedure will not always lead to a load decay response that is more favorable than the legacy conditions; however, it was shown that the best response under legacy conditions is not significantly different than the worst response under optimized conditions.

8. CONCLUSIONS

The majority of studies of self-loosening of bolts in non-permanent applications have focused on long-term service conditions involving temperature and/or cyclic (working or vibratory) loading. Few studies address the short-term behavior of bolted assemblies with gaskets. Although the threaded bolt material is nominally elastic under service conditions, the gasket material undergoes time-dependent deformation. The present study focuses on the conditions that would facilitate that assembly to stabilize its long term behavior with a shortened assembly procedure. Prior to this study, insufficient data were available to make a permanent process change to the legacy re-torque requirements. As such,
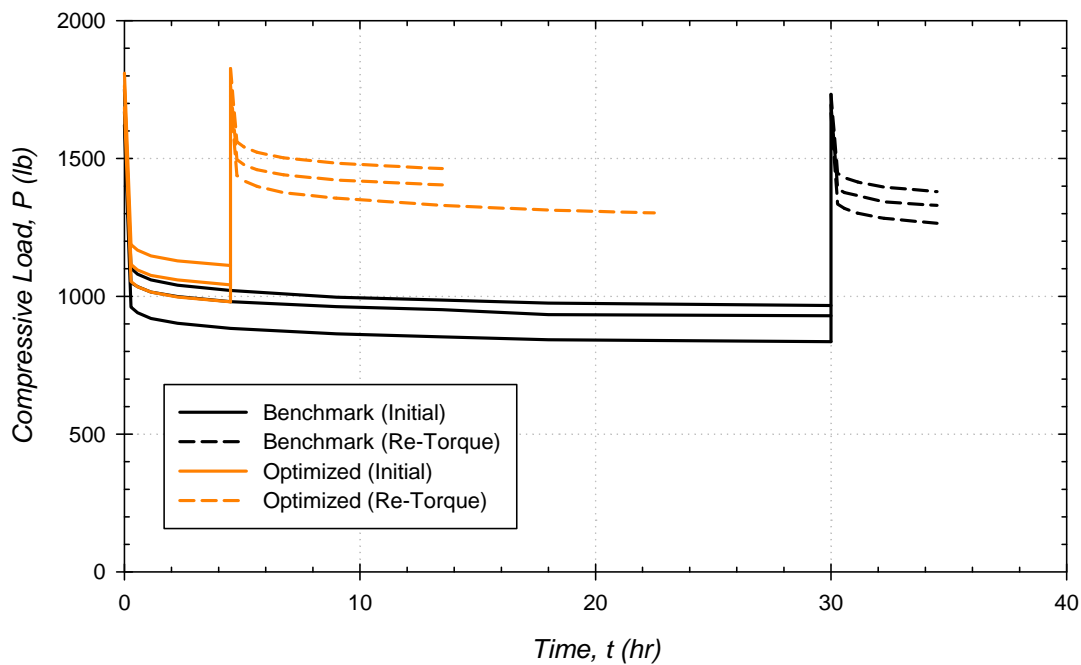
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Figure 9: *Comparison of optimized and benchmark flange response for the STS GUCP.*

identifying the interactions between assembly configuration, initial torque, and re-torque frequency to relaxation behavior of the assembly was identified as a means of reducing the time required before final torque.

Based on the study, the dwell period for the gasket associated with the GUCP can be reduced from 30 *hr* to 4.5 *hr* if a thinner gasket is used. The load decay response of the gasket material as applied in the GUCP was improved by nearly 10%. The experiments, however, were conducted on the basis of two major assumptions related to thermal and mechanical conditions. Specifically, the experiments were carried out in static laboratory conditions (temperature and humidity). Flange joints were subjected to no external mechanical loads aside from those imparted by the bolts. The actual operating conditions of the GUCP include the venting of pressurized fluids at cryogenic temperatures. Future work could be carried out to assess the impact of thermomechanical stresses on the interface.

ACKNOWLEDGMENTS

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