

Torque Tension Testing of Fasteners used for NASA Flight Hardware Applications

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Abstract

The effect of various lubricants and other compounds on fastener torque-tension relationships is evaluated. Testing was performed using a unique test apparatus developed by Posey at the NASA Goddard Space Flight Center. A description of the test methodology, including associated data collection and analysis will be presented. Test results for 300 series CRES and A286 heat resistant fasteners, torqued into various types of inserts will be presented. The primary objective of this testing was to obtain torque-tension data for use on NASA flight projects.

Introduction

Threaded fasteners are used extensively in flight hardware assembly at the Goddard Space Flight Center. The reliability and safety of the assembly is dependent primarily on the preload which is applied by trained and certified technicians using a calibrated torque wrench of the proper size. It has been shown that most of the applied torque is used in overcoming the head bearing and thread friction leaving only a small fraction for fastener elongation or tension resulting in joint pre-load application. The torque tension relationship is therefore highly dependent on the friction coefficients and lubrication applied to the threads and washer-to-bolt head bearing surfaces. Even the most reliable torque application methods have been shown to result in wide scatter and do not accurately predict the joint preload. This can result in premature joint or fastener failure due to over or under estimation of the applied preload. Typical failure mechanisms are vibration loosening, fastener fatigue due to insufficient preload, or joint failure due to excessive preload.

Alan Posey has developed a new bolt preload measurement system which incorporates three miniature load cells and an instrumented torque wrench for measurement of applied torque and joint preload (see Figures 1 and 2).



Figure 1. Bolt Preload Test Fixture & Test Plate

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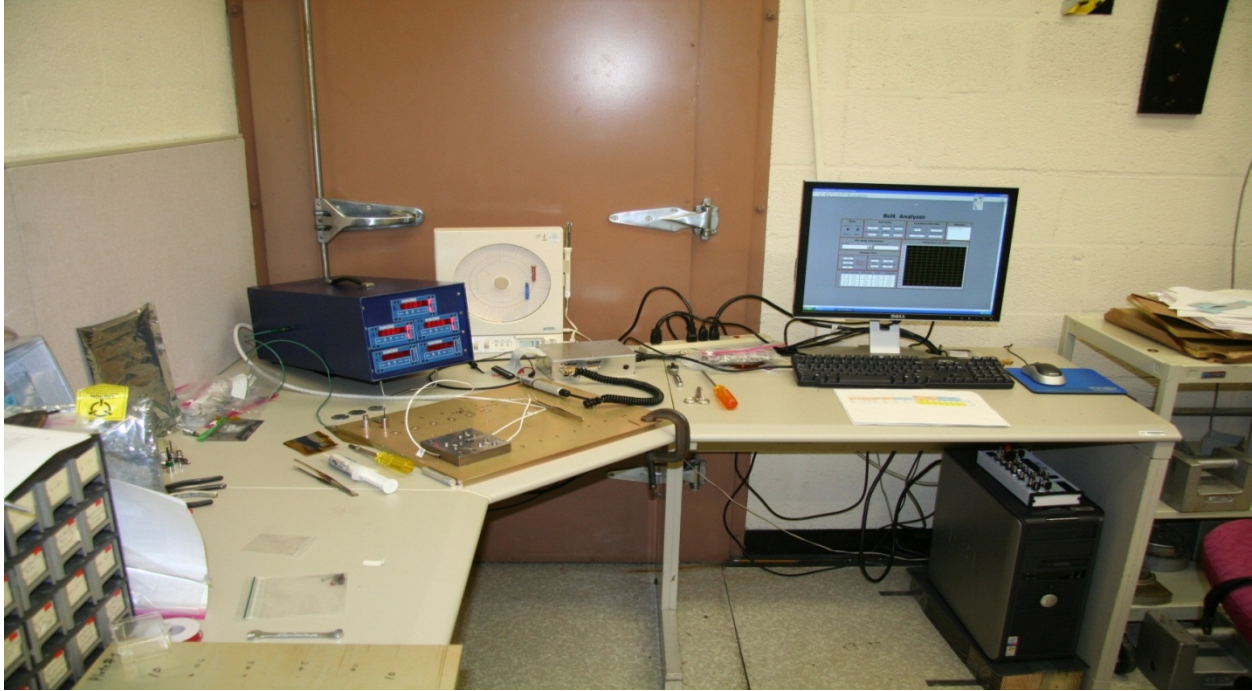


Figure 2. Bolt Preload Measurement System

In the past, one load washer was typically used for torque tension testing but this was not practical for the smaller #0 (1.5-mm) to #6 (3.5-mm) size fasteners as load washers this size were not available. The system consists of three load cells mounted in a high-strength steel fixture plate in an equilateral triangle configuration. A counter-bored bushing, sized for the fastener being tested, is centered in this triangular pattern. The system is connected to a laptop computer with LabVIEW and MATLAB software for data collection and analysis (Figure 3). Fasteners from size #0 (1.5-mm) to ¼-in (6.3-mm) diameter have been tested using this system.

Governing Equation:

- $T=KDP$
-
- $T=Torque,$
-
- $K=Torque$
 $Coefficient,$
-
- $D=Bolt Dia,$
-
- $P=Preload$

Testing to Determine “K”

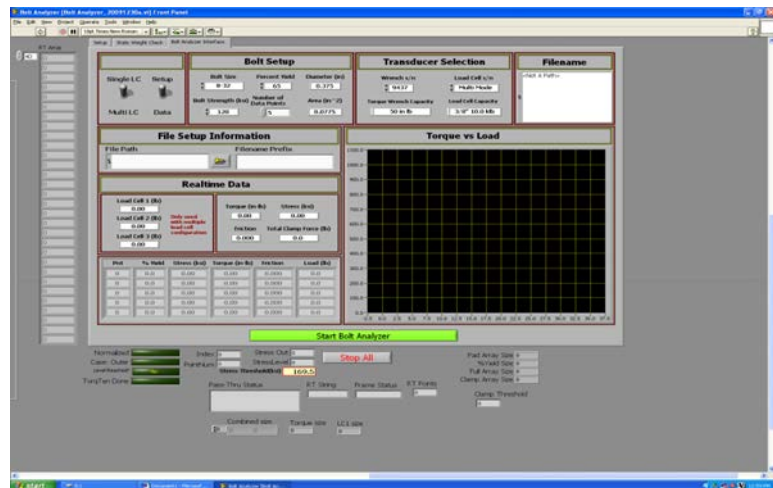


Figure 3. Bolt Analyzer Interface

Test Objectives

The primary objective was to obtain torque-tension data for use of various lubricants such as Braycote 601EF and compounds such as Arathane and Super Koropon. Arathane has been used as a thread locking compound to replace worn out locking features on helical-wire inserts and Super Koropon is used as a corrosion inhibitor/sealer on threaded fasteners and inserts as specified in NASA/JSC PRC-4004, "Sealing of Joints and Faying Surfaces". Some secondary objectives of this testing were to identify the effect of the following variables on torque coefficient (or nut factor) and running torque:

- Multiple cycling of locking inserts.
- Fastener and washer replacement in multiple cycling of inserts.
- The use of multiple lot and or multiple type inserts of a given size.
- The use of ultrasonic cleaning in isopropyl alcohol (IPA) of all hardware as compared to use in as received, un-cleaned condition.

Small Fastener Testing (#2, #4 & #6) (2.2 mm, 2.8 mm & 3.5 mm)

Torque-tension testing of A286 and 300-series CRES fasteners threaded into free running phosphor bronze and silver-plated CRES helical-wire inserts was performed using the system developed by Posey. Fastener testing was performed both with a low outgassing flight-approved lubricant (Braycote 601EF) and dry insertion.

Torque-tension measurements were taken up to 65% of the fastener yield strength which represents the standard preload currently used at Goddard. Both torque and preload were measured at five equally spaced increments up to the target preload. All hardware was ultrasonically cleaned and handled with gloves using flight hardware processes.

Each fastener tested was torque cycled three times while each insert was cycled six times. After three torque cycles into a given insert, the fasteners and washers were replaced with new hardware and re-lubricated. Separate test plates were used for dry and Braycote lubricated samples. Lubrication was applied to the threads and under the fastener head. The fasteners were torqued at a rate of approximately 6 rpm until the target preload was reached. The data tables and plots below provide a summary of the statistics for the torque coefficient (K) for fasteners installed both lubricated and dry into two different types of helical-wire inserts (Silver-Plated CRES and Phosphor Bronze). The standard deviation of the torque coefficient was calculated for each grouping and also combined for all groups. The B-Basis tolerance limit factors of Kmax and Kmin were also calculated based on the sample size and are given in the tables below. Running torque was included in all measured torque values.

Small Fastener Test Results and Conclusions

Table 1 and Figures 4 and 5 provide a summary of the statistics for the torque coefficient (K) for each of the types of fasteners into the different types of inserts (Silver-Plated CRES and Phosphor Bronze).

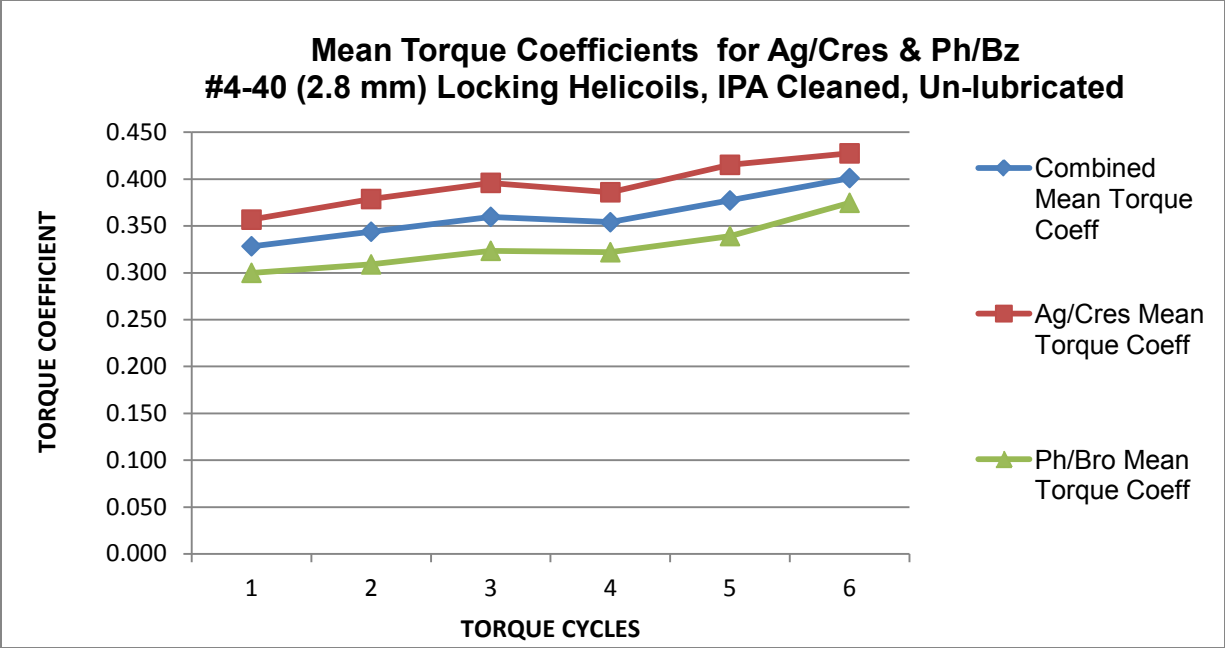


Figure 4. Unlubricated Cyclic Mean Torque Coefficients Example

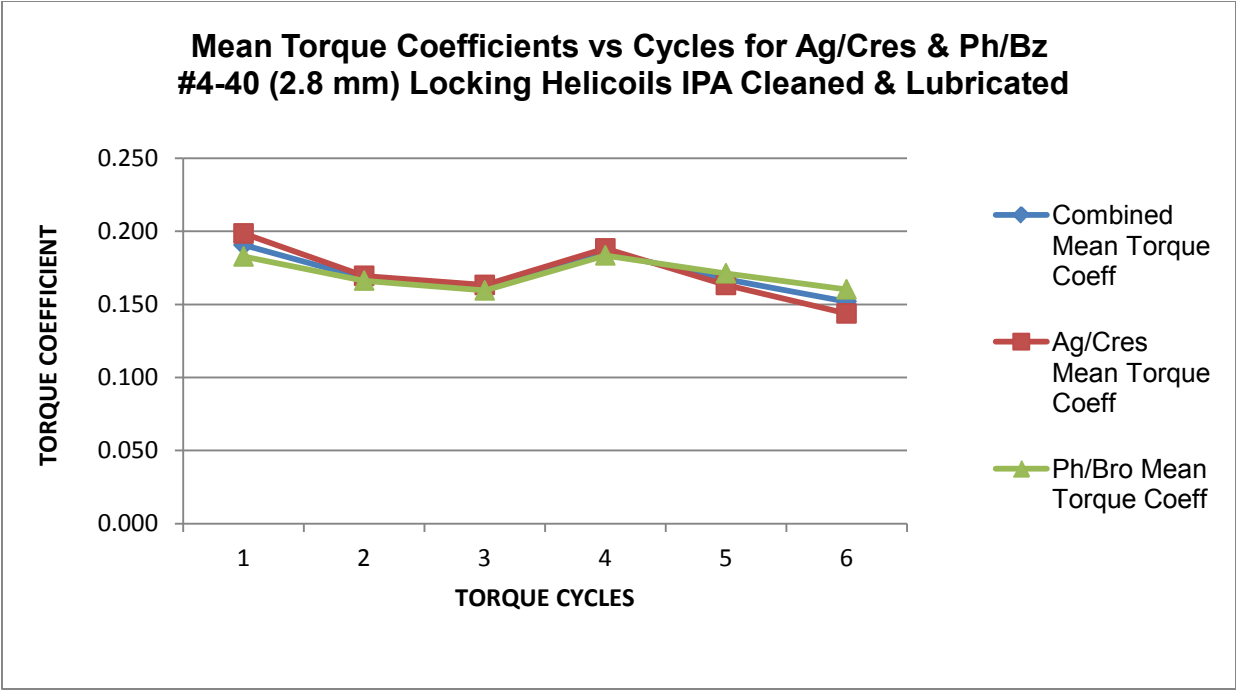


Figure 5. Lubricated Cyclic Mean Torque Coefficients Example

Table 1. Phosphor Bronze Data Summary

Phosphor Bronze Inserts												
Fastener	Wet Lubrication						Dry					
	Mean Torque Coefficient K	STD Dev	No. Samples	Tolerance Limit Factor	B-Basis Limits K-Low	B-Basis Limits K-High	Mean Torque Coefficient K	STD Dev	No. Samples	Tolerance Limit Factor	B-Basis Limits K-min	B-Basis Limits K-max
A286	0.169	0.024	48	1.654	0.129	0.210	0.373	0.084	46	1.664	0.233	0.513
300 CRES	0.174	0.022	36	1.725	0.136	0.211	0.339	0.028	36	1.725	0.290	0.387
NAS1352N A286	0.182	0.032	18	1.974	0.119	0.244	0.401	0.102	17	2.002	0.198	0.605
NAS1101 A286	0.167	0.016	18	1.974	0.135	0.198	0.375	0.071	18	1.974	0.236	0.514
NAS8100/1 A286	0.154	0.017	12	2.21	0.117	0.192	0.326	0.056	11	2.275	0.199	0.453
NAS 1352C 300 CRES	0.170	0.018	18	1.974	0.133	0.206	0.333	0.028	18	1.974	0.278	0.389
MS51957 300 CRES	0.181	0.025	18	1.974	0.132	0.231	0.344	0.028	18	1.974	0.289	0.399
Silver Plated Inserts												
Fastener	Wet Lubrication						Dry					
	Mean Torque Coefficient K	STD Dev	No. Samples	B-Basis Tolerance Limit Factor	B-Basis Limits K-Low	B-Basis Limits K-High	Mean Torque Coefficient K	STD Dev	No. Samples	Tolerance Limit Factor	B-Basis Limits K-Low	B-Basis Limits K-High
A286	0.165	0.019	48	1.654	0.134	0.197	0.422	0.098	45	1.664	0.259	0.585
300 CRES	0.180	0.025	36	1.725	0.137	0.224	0.413	0.081	36	1.725	0.273	0.552
NAS1352N A286	0.173	0.022	18	1.974	0.129	0.216	0.432	0.072	17	2.002	0.287	0.577
NAS1101 A286	0.160	0.013	18	1.974	0.134	0.187	0.444	0.106	18	1.974	0.234	0.653
NAS8100/1 A286	0.162	0.017	12	2.210	0.125	0.199	0.225	0.021	10	2.355	0.175	0.275
NAS 1352C 300 CRES	0.174	0.028	18	1.974	0.119	0.230	0.429	0.074	18	1.974	0.283	0.575
MS51957 300 CRES	0.186	0.021	18	1.974	0.145	0.227	0.396	0.086	18	1.974	0.226	0.566

Conclusions and Observations based on the results shown in Table 1:

1. For dry un-lubricated cases, the torque coefficient was found to increase with cycles, whereas for the lubricated cases the reverse was true.
2. The dispersion (standard deviation) of the torque coefficient for all the Dry groups of fasteners was much greater for the dry installation versus the lubricated installation. The smaller dispersion for lubrication make it a better choice (when acceptable to the project) than installing dry since there

is less uncertainty with the torque-tension relationship

3. The torque coefficients for dry silver-plated CRES inserts were higher than for phosphor bronze inserts. In addition, the dispersion was also higher for the dry silver-plated CRES inserts. This was more pronounced for larger size fasteners and goes counter to the assumption that silver plating will act as an effective lubricant. For lubricated samples there was little difference.
4. The torque coefficients for smaller fasteners were found to be higher than those specified by the Goddard Torque Guideline. In this document the lubricated torque coefficient is specified at 0.15 and dry coefficient at 0.2. Based on the small fastener test results, these values were revised to a wet coefficient of 0.18 and dry coefficient of 0.37. Also, based on un-cleaned test results, a coefficient of 0.25 was specified for dry un-cleaned samples.

Arathane Testing

The purpose of this testing was to determine the differences in torque coefficient when applying Arathane 5753 thread locking compound versus Braycote 601EF lubricant to the fasteners at installation. The use of Arathane as a secondary locking feature was proposed when locking inserts were worn due to repeated torque application cycles. The test sequence was as follows:

- First, the locking phosphor bronze inserts were worn by (10) torque application cycles to 65% yield. This was performed for three different size inserts, #8 (4.2 mm), #10 (4.8 mm) and ¼ inch (6.3 mm) with Braycote lubrication applied to the fastener threads and washer to bolt head bearing surface for first cycles only.
- During each of the (10) torque application cycles, torque-tension measurements were recorded.
- After ten cycles, the worn insert was thoroughly cleaned and a new fastener and washer were installed with Arathane applied to threads and washer to bolt head bearing surface.

Also investigated was the case where a new fastener is installed into a new locking phosphor bronze insert with both Arathane and Braycote. Two different cleaning agents, (IPA and HFE7100) for removal of the Braycote lubricant from worn inserts, were also investigated.

Arathane Test Results and Conclusions

The average torque coefficients (Kmean) were determined by two methods as follows:

1. First method was to use the average total torque at the target preload of 65% fastener yield.
2. The second more involved method was to perform a linear regression curve fit of actual test data and determine the torque coefficient from the slope of the linear regression curve. As shown in the Table 2, there was little difference between the two methods for the various data sets.

Table 2. Torque Coefficient Comparison: Average vs Linear Regression Method

Configuration	Ave Torque Coeff @ 65%	Ave Torque Coeff Linear Regression (LR)	% Difference of Methods
Worn #8 Braycote	0.145	0.137	5.4
Worn #8 Arathane	0.284	0.277	2.6
Worn #10 Braycote	0.175	0.168	4.2
Worn #10 Arathane	0.314	0.312	0.6
Worn 1/4" Braycote	0.227	0.219	3.5
Worn 1/4" Arathane	0.316	0.321	1.8

A comparison of torque coefficients for use of Arathane and Braycote is shown in Figure 6. The cyclic data was combined into one data set for each fastener/insert size to generate this comparison data plot.

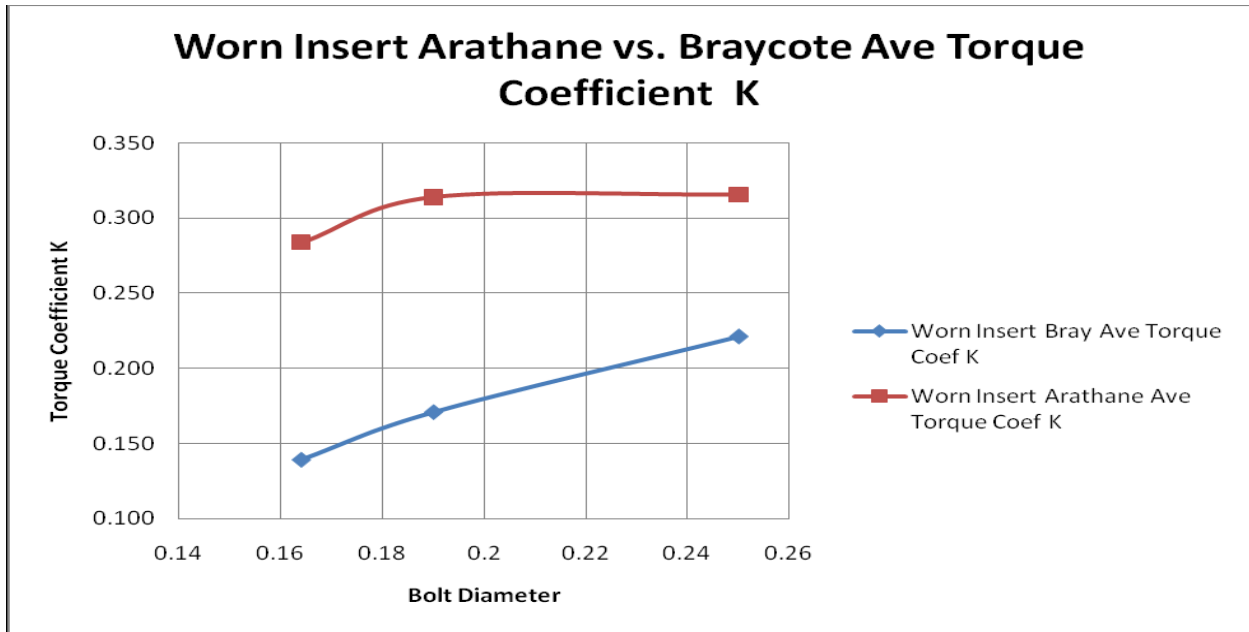


Figure 6. Arathane and Braycote Torque Coefficient Comparison

A typical plot of torque coefficients for individual torque application cycles is shown in Figure 7 for #10-32 size fasteners. Cycles 1-10 are Braycote wear cycles, cycle 11 is for a new fastener and washer used in the worn insert with Arathane and cycle 12 for a new fastener and washer used in a new insert with Arathane. The Kmax and Kmin torque coefficients are based on B-basis calculations similar to those used for small fasteners.

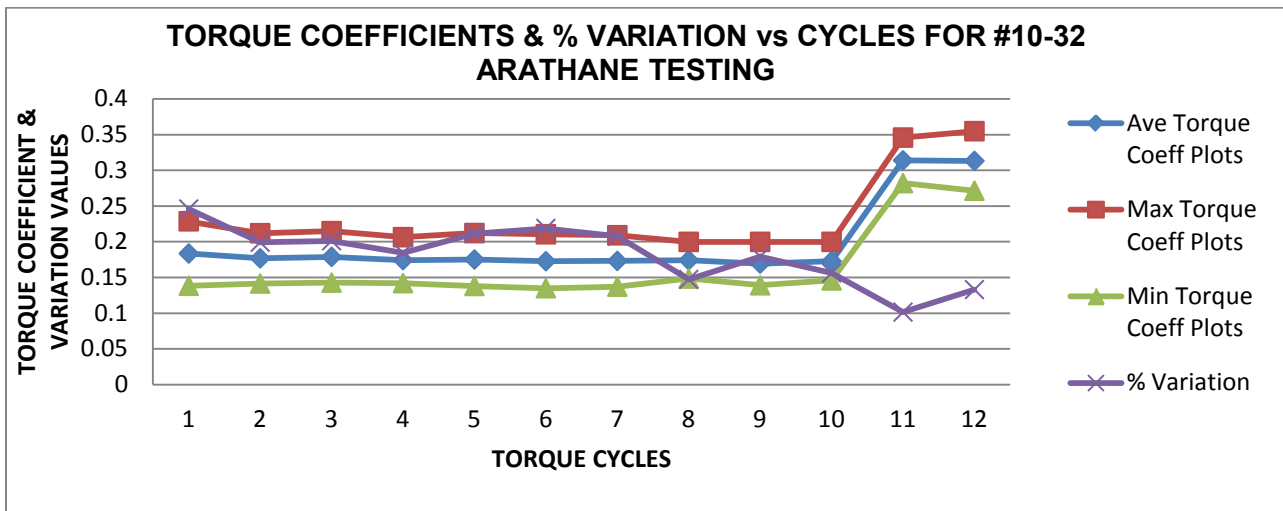


Figure 7. Cyclic Torque Coefficients, Braycote (1-10), Arathane (11-12)

The variation curve in Figure 7 is based on data scatter or difference from Kmean and was calculated as follows:

$$\text{Variation} = (K_{\text{max}} - K_{\text{min}}) / (2 * K_{\text{mean}})$$

Table 3. Data Summary Tables for A286 Fasteners

Fastener	Braycote Lubrication Phosphor Bronze Insert (Worn)						% Below mean	% Above mean
	Mean Torque Coefficient Kmean	STD Dev	No. Samples	Tolerance Limit Factor	B-Basis Limits Kmin	B-Basis Limits Kmax		
#8 - 0.25 in (4.2 – 6.3 mm)	0.182	0.039	300	1.417	0.127	0.238	30.5	30.5
Fastener	Arathane Installation Phosphor Bronze Insert (Worn)						% Below mean	% Above mean
#8 - 0.25 in (4.2 – 6.3 mm) IPA & HFE Clean	0.304	0.028	30	1.777	0.254	0.355		

Fastener	Arathane and Braycote Comparison New Phosphor Bronze Insert						% Below mean	% Above mean
	Mean Torque Coefficient Kmean	STD Dev	No. Samples	Tolerance Limit Factor	B-Basis Limits Kmin	B-Basis Limits Kmax		
Arathane #8 - 0.25 in (4.2 – 6.3 mm)	0.322	0.024	30	1.777	0.278	0.365	13.5	13.5
Braycote #8 - 0.25 in (4.2 – 6.3 mm)	0.205	0.044	30	1.777	0.128	0.283	37.7	37.7

The following conclusions were noted based on the above test results and Figure 8 for combined Arathane and Small Fastener Testing which were both based on similar A286, 160-ksi (1.1-MPa) strength fasteners installed into Braycote 601EF lubricated phosphor bronze inserts.

1. For both worn and new inserts, the torque coefficient for Arathane installed fasteners was significantly higher than the same size fastener lubricated with Braycote.
2. For worn inserts, the Arathane torque coefficient was ~71% higher than Braycote (K: 0.304 vs. 0.178). It is recommended that for worn inserts the torque should be based on a torque coefficient of 0.30 when Arathane is used.
3. For new inserts, the Arathane torque coefficient was ~57% higher than Braycote (K: 0.322 vs. 0.205). It is recommended that for new wire inserts the torque should be based on a torque coefficient of 0.32 when Arathane is used.
4. There was not an appreciable difference of the Arathane torque coefficient for those inserts cleaned with IPA vs. HFE7100.
5. The torque coefficient was lowest for the #8 (4.2-mm) fasteners and highest for the 0.25-in (6.3-mm) diameter fasteners.
6. If all the data are combined the resulting average torque coefficient is 0.180. As previously noted, the Goddard torque spec tables in 540-PG-8072.1.2 specify a torque coefficient of 0.150 for lubricated fasteners. The data show that for a very commonly used (@ GSFC) combination of

A286/160 ksi (1.1 MPa) fasteners installed with Braycote 601EF into phosphor bronze wire inserts, a change to the Goddard Mechanical Systems Division torque spec should specify a torque coefficient of 0.18

- Also, the B-Basis scatter of the Torque coefficient is $\pm 30\%$. Typically a torque coefficient range of $\pm 25\%$ is commonly used at GSFC.

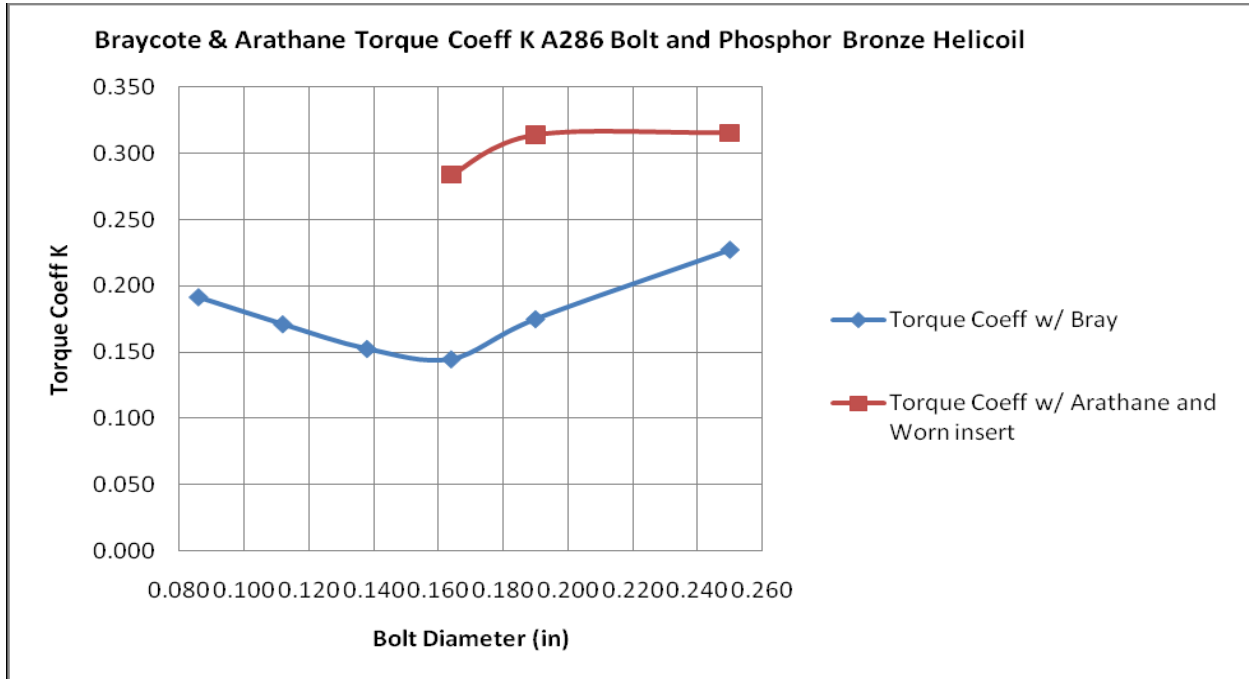


Figure 8. Combined Torque Coefficients Arathane & Small Fastener Testing

“ORION” Super Koropon Testing

ORION is a manned spacecraft proposed for beyond low Earth orbit that is being designed and built jointly by Lockheed Martin for NASA and the European Space Agency. Two phases of torque-tension testing were performed for ORION. Phase I (6) cycle testing was performed to determine if as-received and un-cleaned fasteners, inserts and washers could be used for assembly of flight hardware. All inserts were received with molybdenum disulfide dry film lubricant applied to the threads by the manufacturer. The fastener and insert combinations tested are shown in Table 4. In addition to the different insert types and cleanliness, various lot numbers for each size and type were also tested to determine the effect on torque coefficient.

Table 4. Test Hardware Phase I & II Fasteners/Inserts & Washers

		Fasteners		Washers	
1	#10-32 Hex Head A286	NAS6703U12		LMC21D5AC3C/A286 CS	
2	1/4-28 Hex Head A286	NAS6704U12		LMC21D5AC3C/A286 CS	
	Keensert	Type	HD	EXHD	LW
1		#10-32	MS51831CA201L	MS51832CA201L	MS51830CA201L
2		1/4-28	MS51831CA202L	MS51832CA202L	

The Phase I (6) cycle test sequence was as follows:

- One half of the fasteners/inserts and washers were cleaned in IPA and the other half were tested as received and un-cleaned.
- Super Koropon, an epoxy-polyimide corrosion inhibitor/sealer for threaded assemblies, was applied to the fastener and washer bearing surfaces of all Koropon installed samples. Fastener threads were not lubricated with Koropon.
- Some cleaned and un-cleaned/as received sample sets were also tested dry without Super Koropon applied to fastener and washer bearing surface.
- All inserts were torqued to 65% fastener yield for total of six cycles with fastener and washer replacement after the third cycle.

Phase II (10) cycle testing was performed to determine the effect of ten cycles on running torque and also if additional benefit could be derived by lubrication of fastener threads with Braycote. All hardware was tested as received and un-cleaned. Super Koropon was applied to fastener and washer bearing surfaces of Koropon samples with some sample sets also being tested dry, without Koropon. Some fastener threads were also lubricated with Braycote to determine the effect on torque coefficient. Two types of Braycote lubricant were tested, Type 601 for anti-rust and Type 602EF with moly disulfide for anti-galling. Phase II test sequence was as follows:

- As received dry film lubricated inserts with no additional Braycote lubrication.
- As received dry film lubricated inserts with fastener threads lubricated with Braycote 601.
- As received dry film lubricated inserts with fastener threads lubricated with Braycote 602EF.
- Fasteners were replaced only if running torque was less than 3 in-lb (0.3 N-m).

Phase I and Phase II Test Results

The data plots and tables below provide a summary of the statistics for Phase I and II testing. Figure 9 and Table 5 summarize the Phase I (6) cycle test results. Figure 10 and Table 6 summarize the Phase II (10) cycle results.

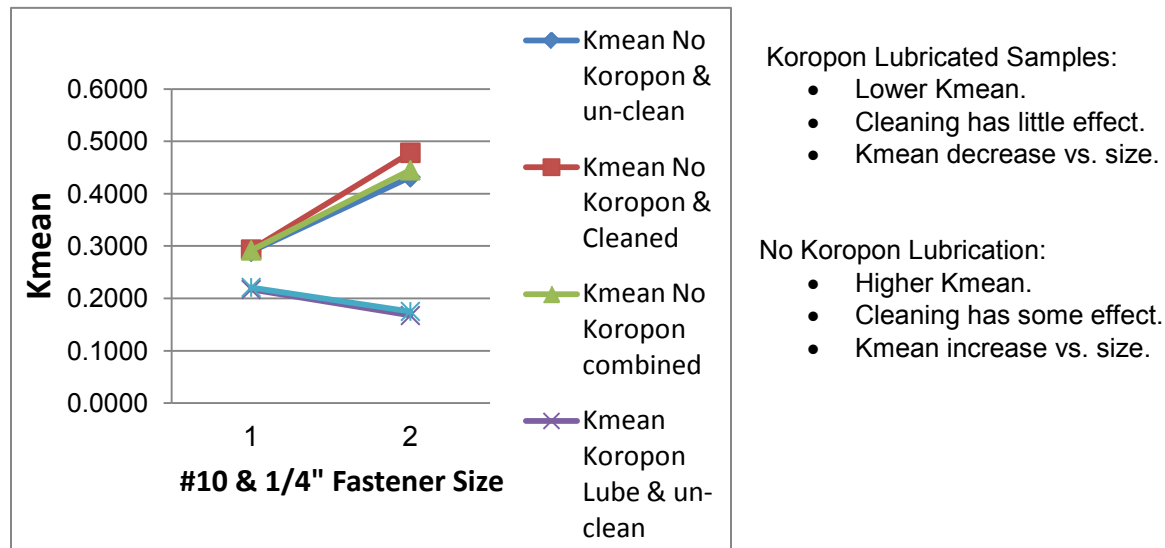
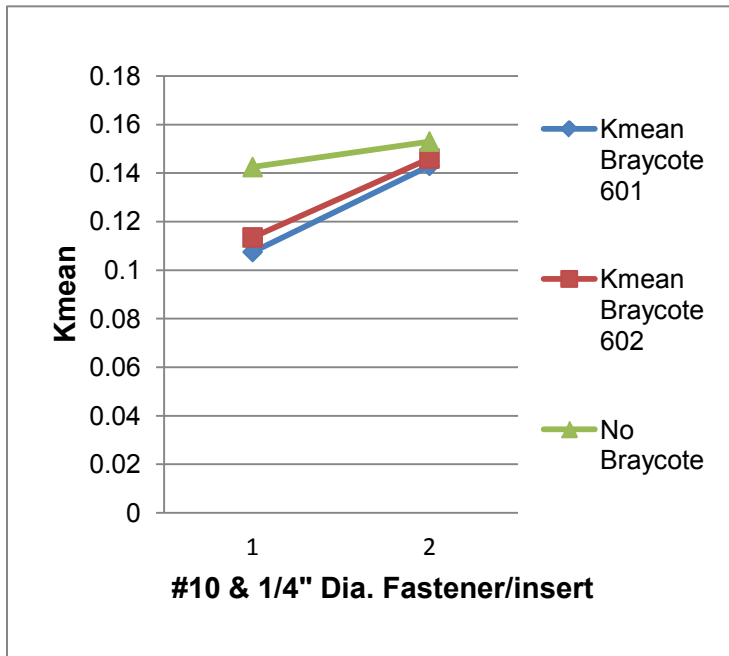


Figure 9. Kmean with and without Koropon Lube

Table 5. Phase I (6) Cycle Statistics for #10-32 (4.8 mm) & 1/4-28 (6.3 mm) Fasteners

Koropon Lube cleaned and un-cleaned						
	Koropon/un-clean		Koropon/cleaned		Koropon/Combined	
Size	#10	1/4"	#10	1/4"	#10	1/4"
Kmean	0.217	0.167	0.221	0.175	0.219	0.170
Kmax	0.273	0.203	0.270	0.214	0.268	0.208
Kmin	0.161	0.132	0.172	0.137	0.169	0.132
Variation	0.259	0.212	0.223	0.219	0.226	0.223
N=cycles	60	96	48	90	108	186
No Koropon Lube #10, cleaned and un-cleaned						
	No Koropon/un-clean		No Koropon/cleaned		No Koropon/Combined	
Size	#10	1/4"	#10	1/4"	#10	1/4"
Kmean	0.289	0.432	0.293	0.478	0.292	0.445
Kmax	0.393	0.554	0.390	0.632	0.384	0.568
Kmin	0.186	0.309	0.196	0.325	0.200	0.322
Variation	0.359	0.284	0.331	0.321	0.316	0.277
N=cycles	30	30	54	12	84	42



Additional Braycote Lubrication applied to fastener threads is beneficial for smaller size #10-32 (4.8 mm) fasteners but less so for larger size 1/4-28 (6.3 mm) fasteners.

For larger size fasteners, the head-to-washer bearing surface becomes more dominant and thread friction is less of a factor.

Use of Braycote 601 or 602EF are equally effective with respect to Kmean.

Figure 10. Kmean for Koropon with and without Braycote Lube

For Fastener Statistics in Table 5 for (6) cycle test results and Table 6 for (10) cycle test results, the data variation was calculated as follows:

$$\text{Variation} = (K_{\text{max}} - K_{\text{min}}) / (2 * K_{\text{mean}})$$

Table 6. Phase II Kmean for Koropon with and without use of Braycote

Size	EXHD & HD Keenserts Koropon Lube Applied							
	Braycote 601		Braycote 602		Combined		No Braycote	
	#10	1/4"	#10	1/4"	#10	1/4"	#10	1/4"
Kmean	0.108	0.143	0.114	0.146	0.111	0.144	0.143	0.153
STDVA	0.013	0.031	0.024	0.022	0.019	0.027	0.025	0.028
Kmax	0.137	0.204	0.168	0.191	0.149	0.195	0.193	0.210
Kmin	0.078	0.082	0.059	0.102	0.072	0.094	0.092	0.097
Variation	0.274	0.427	0.480	0.305	0.351	0.351	0.356	0.369
N	20	50	20	40	40	90	40	50

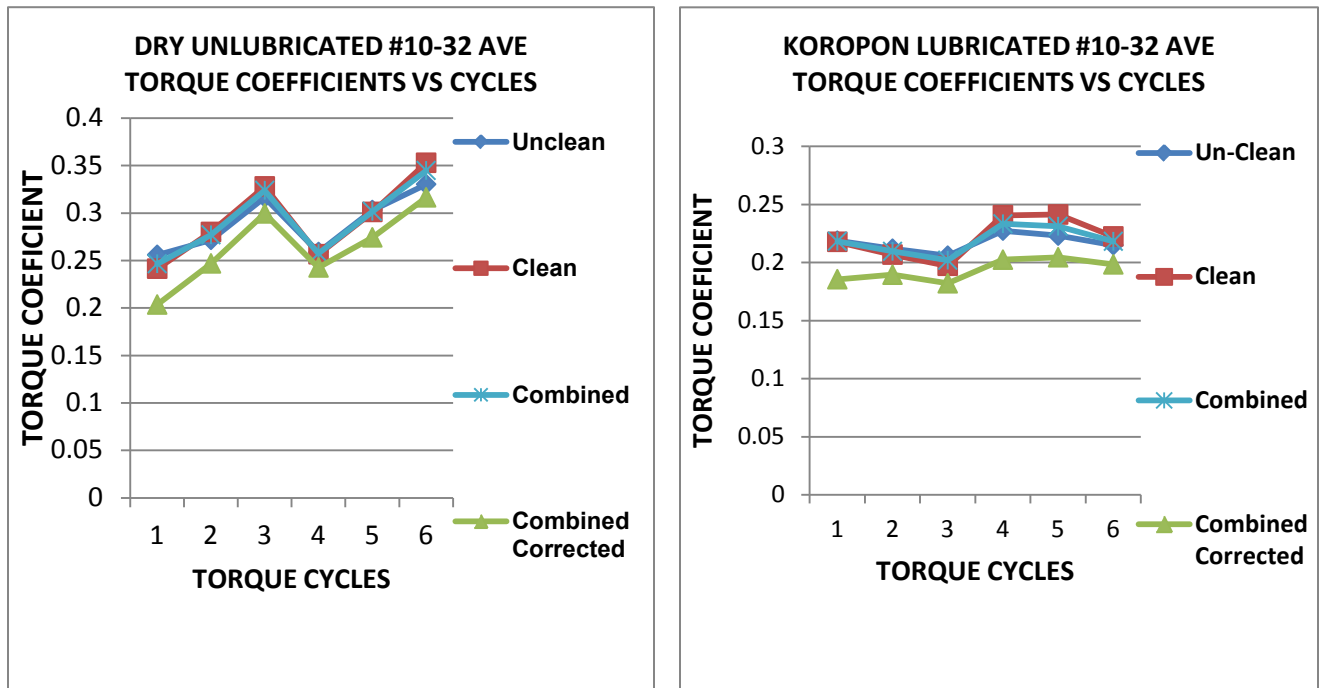
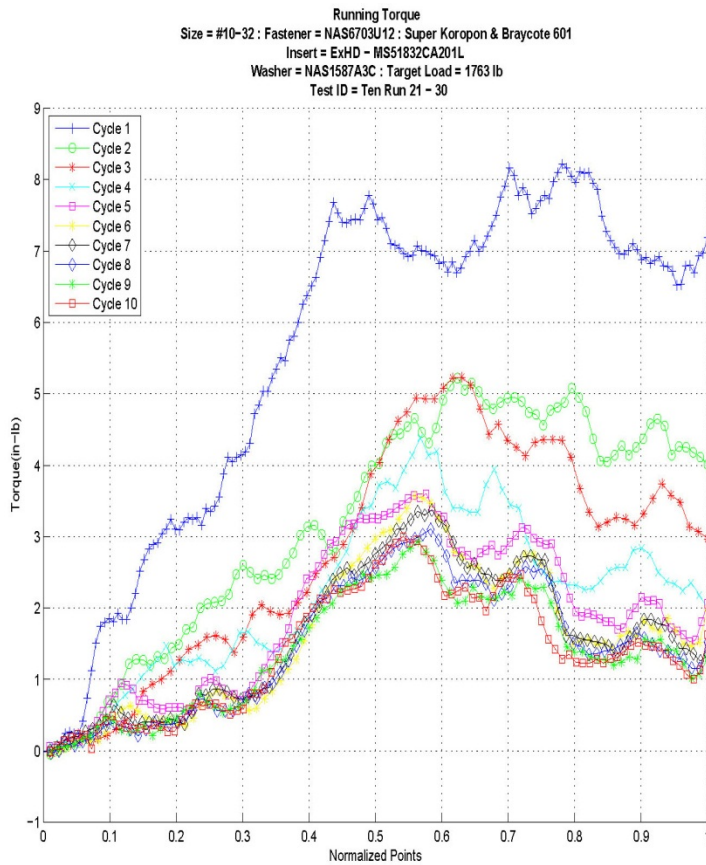


Figure 11. Cyclic Kmean for Un-lubricated and Lubricated Samples

The following generalized conclusions can be drawn based on the six and ten cycle testing:

1. For Dry/no-Koropon, Kmean and Variation were found to increase with fastener size. The reverse was true for use of Koropon.
2. There was little difference in Kmean for cleaned and un-cleaned test samples.
3. Removal of running torque was found to reduce Kmean by as much as 20%, refer to corrected plots, Figure 11.
4. The Kmean vs. cycles for un-lubricated samples was found to increase. For lubricated samples, the trend was reversed (refer to Figure 11). Replacement of fastener, washer and re-lubrication after third cycle is beneficial in reducing Kmean.
5. For cycles 1-6 into the same insert without Koropon, there was a large change in torque coefficients. With Koropon use, there was little change.
6. Running Torque was reduced significantly after first torque application but remained above a minimum of 3 in-lb (0.3 N-m) in all but (3) sample sets, Figure 12.



With Braycote Lubrication

Running Torque 8 in-lb (0.9 N-m) max. Is 30% less than 12 in-lb (1.4 N-m) for no Braycote lube.

Follow-on cycles are also lower due to the lubrication effect but remain above minimum required 3 in-lb (0.3 N-m).

Figure 12. Typical Running Torque Plot for (10) Cycles, Koropon + Braycote Lube

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