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H-Canyon Jumper Gasket Sealing Evaluation

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REVISIONS

Revision 0: Initial, July 2022
Revision 1: Customer-requested changes: November 2022

a. Added additional approvers.
b. Addressed review comments and accepted resolutions developed after initial issue that required several changes, are documented in the Savannah River Site Electronic Notebook (ELN), Experiment L0833-00318-01, "Hanford Connector Gasket Evaluation," 2022.

EXECUTIVE SUMMARY

H-Canyon Documented Safety Analysis approved December 2019 [1] credits the leak integrity of H-Canyon (HCA) process tanks, piping, and jumpers in preventing the release of radioactive material in a post seismic environment. Demonstration of leak tightness capability for this equipment was achieved through substantial analytical effort. However, one potential weak point that affects leak integrity exists at the gasketed joint between Hanford Connectors (HC) and nozzles. Review of the HCA Crane Log over a three-year period indicates the HCs periodically leak [2]. Savannah River National Laboratory (SRNL) was requested to perform gasket compression tests that evaluate gasket relaxation characteristics, i.e., creep, and provide improvements to the HC installation process that can reduce or eliminate the frequency of leaks at HCs. A HC torque value of 312 ft-lbf [3] is the target value used because it is the minimum torque value, with 95% confidence, when an unlubricated HC is impacted for standard sealing period of 9 seconds.

In the HCA pipe-jumper connections are installed remotely by using HCs. HCs inherently add to the uncertainty of a gasketed joint because a calibrated torque value cannot be applied. The gasket material is a special material made of asbestos-fiber impregnated with Teflon. This material has been used for decades and generally performs well but does leak intermittently as gaskets creep and preloaded torque is lost. Gasket types are either snap-ring (SR) or lampshade (LS). Both gasket types cover the same seating area. The SR gasket is designed to remain with the jumper when the jumper is removed leaving the nozzle faces clean of any debris. SR gaskets are initially installed when the jumper is fabricated. Changing gaskets is time consuming and the radioactive environment presents risks to personnel. When jumpers are removed LS gaskets could be used to better seal the connection to reduce down time and ALARA concerns. That is, an LS gasket would be remotely positioned over the nozzle and the HC reinstalled.

Testing also included two situations not typical of plant operation. One situation was the use of the non-standard double-layered gaskets (DG), and the other situation was the use of a LS without removal of the installed SR gasket. The DG was used when the supply of LS gaskets ended, so that testing could continue. It was of interest to demonstrate this gasket's creep response because the DG, which was two gaskets glued together, was thicker than the LS gasket and the thicker material was expected to elicit a greater creep characteristics. The second situation of using two gaskets together by installing an LS gasket without removing the installed gasket is not allowed by the ASME Codes. However, by demonstrating the creep history of such a gasket arrangement it could be considered as an option that could possibly seal a connection while significantly reducing operational down time and personnel risk. Forty tests were conducted, and the overall results demonstrate the initial applied force and how the gasket changes with time. The change in sealing force, in terms of torque, was then measured to obtain a force history as the gaskets creep. This report documents the results of those tests as well as the method used to perform the tests.

Results:
1. The torque response of using either a SR gasket (0.105-inch thick) or a LS gasket (0.150-inch thick) was the same, so either gasket is sufficient to seal a HC by themselves.
2. Approximately 15% of the force from the torquing of a fresh SR gasket is lost in the first 5 minutes, but the loss may be as high as 33%.
3. Within the first 24 hours the sealing force from the initial torque for a fresh SR gasket decreases as much as 38%.
4. Within the first 24 hours the sealing force from a re-torque of a new SR gasket drops by up to 20%. That is, retorquing a new gasket improves and reduces the loss rate of the sealing force.
5. Tests with the thicker double-layered DG (0.190 inch) had conflicting results from good to poor performances; therefore, their use is not recommended.

6. Adding a fresh LS gasket, without removing an existing SR gasket, which has been previously torqued, leads to a sealed connection that still retains approximately 80% of the initial applied torque after 6 days. Adding a LS gasket to the previously used SR gasket is as good as changing a leaking SR gasket for a new SR gasket.
7. Retorquing the SR+LS gasket arrangement reduces the loss of applied torque to better than 85%, even after several weeks. Results show retorquing can slow the loss to maintain the applied torque to better than 70% of the initial value for more than a year.

Conclusions:

1. Thicker LS gaskets, termed LS-n gaskets (i.e., 0.150”) are acceptable for use.
2. Procedure modifications required for reducing HC leaks:
    1. After the initial torque of a HC with a new SR or LS gasket, retorque the HC no sooner than 8 hours from the time of the initial torque.
    2. If a LS is used without removing the SR, two retorques of the HC should be performed. The first retorque to be performed no sooner than 8 hours from the initial torque and the second retorque no sooner than 8 hours from the first retorque.

Recommendations:

1. The applied system pressure during testing was not prototypic, starting high and slowly decaying with time. Actual system pressures must fluctuate as flows start and stop through pipes. In future tests it would be prudent to determine actual system pressures to be more prototypic. For example, the flow system pressure through HC should be low when nothing is flowing, which may be most of the time. In general, before further, similar testing, it would be beneficial to determine the prototypic environment. Unless the pressure is made more prototypic it may be better to not apply a pressure at all to eliminate the unknowns when evaluating changes in sealing forces on gaskets.
2. Gaskets relax with time causing the applied torque to drop. While most of the loss of applied load occurs in minutes and hours of the initial load, the loss slows but never stopped during the durations tested of up to 22 days. Longer-term tests, e.g., 6 to 8 weeks, should be performed to better predict the long-term loss with time.
3. Always install a new SR gasket after a joint containing a SR+LS gasket arrangement begins to leak. Trying to separate a LS gasket from a SR gasket causes damage to both seals.
4. Developing timetables to record when a HC is sealed and when it leaks would be useful to proactively retorque seals before a leak occurs to reduce the frequency of leaks throughout HCA. (A similar recommendation can be found in Reference [4].)
5. Without results from the preceding recommendation, a reasonable timetable to periodically retorque seals to minimize leaks could be developed from Table 4.

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LIST OF ABBREVIATIONS

ALARA	As Low As Reasonably Achievable
DAS	Data Acquisition System
DG	Double Gasket (nominally 0.190-inch thick)
DSA	Documented Safety Analysis [1]
ELN	Electronic Notebook (Archive to record experiment data and calibrations)
HC	Hanford Connector
HCA	H-Canyon
LS	Lamp-Shade Gasket Assembly
LS-n	New Type of Lamp-Shade Gasket (nominally 0.150-inch thick)
LS-o	Original Type of Lamp-Shade Gasket (nominally 0.120-inch thick)
M&TE	Measurement & Testing Equipment (SRNL Record System)
PI	Principal Investigator
SR	Snap Ring Gasket (nominally 0.105-inch thick)
SRNL	Savannah River National Laboratory
TD	Torque Divisor (correlates measured force on the HC to torque from calibration, lbf/ft-lbf)

1.0 Introduction

H-Canyon Documented Safety Analysis approved December 2019 [1] credits the leak integrity of H-Canyon process tanks, piping, and jumpers in preventing the release of radioactive material in a post seismic environment. Demonstration of leak tightness capability for this equipment was achieved through substantial analytical effort. However, one potential weak point that affects leak integrity exists at the gasketed joint between Hanford Connectors (HC) and nozzles. Review of the H-Canyon Crane Log over a three-year period indicated that HCs on process jumpers periodically leak [2, 5]. The SRNL was requested [6] to measure applied loads to HC and to measure how those loads change with time as sealing gaskets relax, or creep [7], as well as provide improvements to the HC installation process that can reduce or eliminate the frequency of leaks at HCs.

The load changes as relaxation occurs in the asbestos impregnated gaskets supplied by the American Braiding and Manufacturing Company that provide a seal for joints between HCs and wall/tank nozzles. With time and pressure, the gaskets relax and degrade causing joints to leak. Tests were performed to evaluate the changing stress in the HCs used to hold joints tightly together and to estimate when initial applied torque drops to 312[1] ft-lbf. Those tests quantify the gasket creep from applied stress by the connectors that causes a drop in the sealing force; thus, eventually leading to seals to leak. This report documents the results of those tests as well as the method used to perform the tests.

Many Canyon connections are made remotely with the use of Jumpers. Jumpers are generally sections of pipe with a single lifting point used to connect vessels and other pipes. Frequently the ends of jumpers contain a device called a Hanford Connector. The HC is used to mate to a pipe nozzle in order to seal the connections. That is, a HC is an extremely useful tool to hold pipe fittings together where access to fittings is limited due to dangerous environments, which pose risks to personnel, like when radioactivity is present. The HC holds a pipe joint closed to prevent leaks during normal operation. However, leaks do periodically occur with the large number of HC joints in operation in HCA. To repair leaky connections, or to configure piping or vessels within the canyon, the HC can be opened remotely. Figure 1 shows one type of HC.

In this figure, a pipe nozzle sits below the HC and is shown just before the joint is closed and sealed to allow the flow of material through the 90-degree connection of two pipes. Between the HC and the nozzle is a gasket to prevent leaks. The three clamps (jaws) on the HC are opened to allow the HC to be placed on the nozzle. Then the HC screw is rotated, which closes and retracts the jaws, pulling the nozzle flange against the gasket, which is retained against the connector block by a metal snap ring. Once tightened and leak free the HC is left in place until the joint needs to be opened.

[1] Within a 95% confidence level 312 ft-lbf is the value of the lowest torque obtained when applying a 9-second impact to an unlubricated 3-inch HC [1, 3] and the minimum value to maintain a connection leak tight [8].

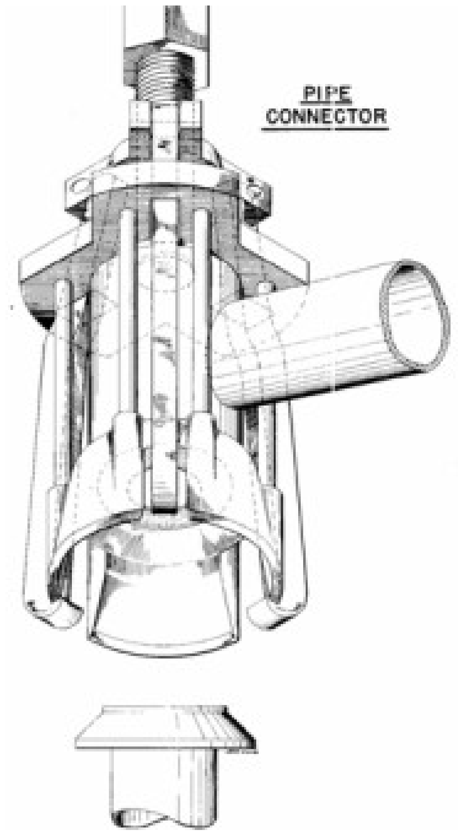

Figure 1: Hanford Connector being lowered onto a pipe nozzle

Figure 2, from reference [9], shows a 90° section view of the HC in place and the joint is sealed due to the installed gasket being held tightly in place by the three HC jaws, of which only one is seen in **Figure 2.**

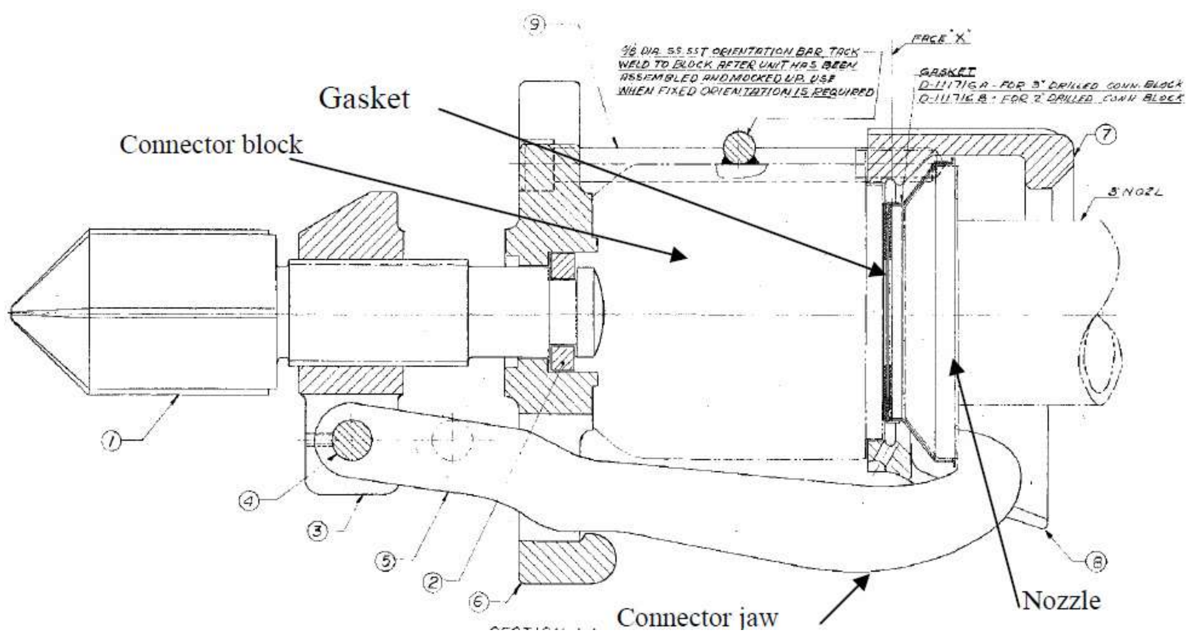

Figure 2: Side view of typical Hanford Connector applied to a nozzle joint

Another view of the HC with the gasket arrangement is shown in Figure 3, which is a sketch of a profile of the HC illustrating the lineup of a standard gasket. The metal snap ring is used to hold the gasket, referred to as a SR gasket, in place. The pipe nozzle is held tightly in place against the SR gasket to seal the joint when the HC jaws are pulled up against the nozzle flange.

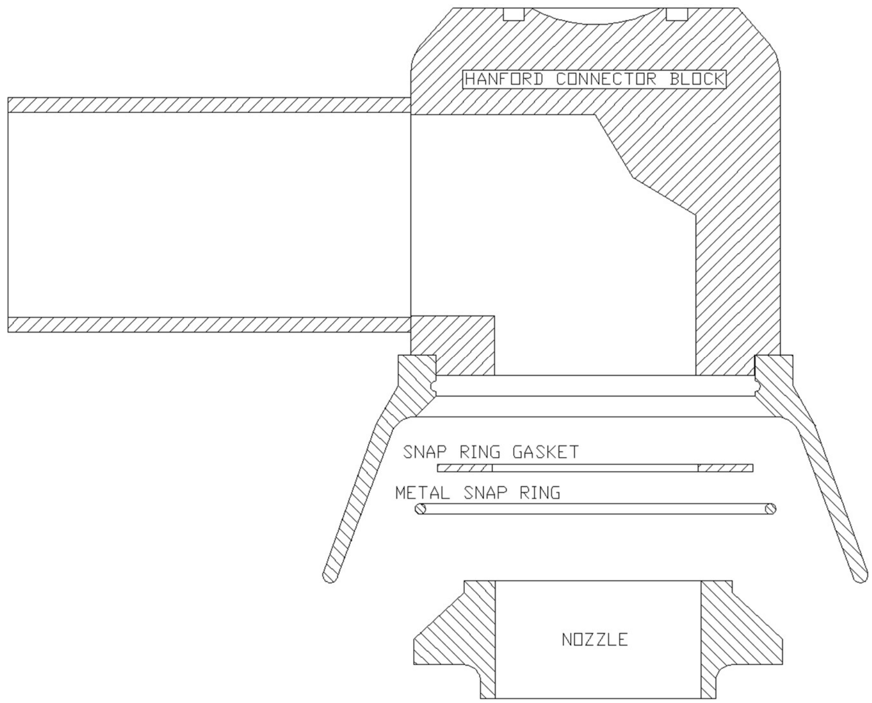

Figure 3: Side view of typical Hanford Connector applied to a nozzle joint with standard gasket and metal snap ring to hold gasket in place

Figure 2 and Figure 3 show how a HC is generally set up to seal a connection; however, when the SR gasket is found leaking the leak needs to be stopped. The first step is to simply re-tighten the HC slightly with an impact wrench. This impacting is allowed to be done twice to stop the leak. However, if the second attempt fails to seal the connection the HC needs to be removed and sent to maintenance to replace the SR gasket. Changing the gasket takes the connection out of service, is time consuming, and increases personnel risk during the actions needed to change the seal. To minimize operational down time and personnel risk another gasket arrangement is planned. That is, the remote installation of an LS gasket.

Replacing a gasket is principally a manual operation, but fortunately in 2008 [9] a Remote Gasket Replacing Tooling system was devised to change a gasket, to reduce personnel radiation exposure. While this system was demonstrated to successfully change gaskets, the process is still time consuming. Therefore, another method was devised to seal leaking joints. Instead of opening and relocating a jumper to change a gasket, a faster and safer method would be preferred, that is, the remote placement of an LS gasket. The gasket arrangement is shown in Figure 4 as a sketch and its placement is shown in Figure 5.

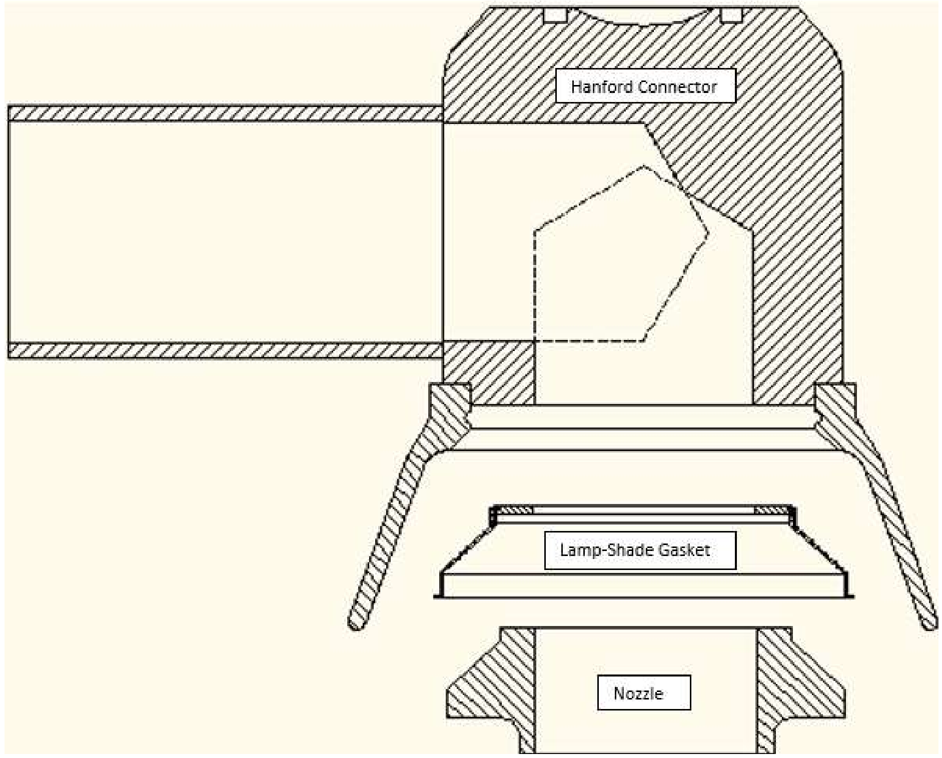

Figure 4: Side view of typical Hanford Connector applied to a nozzle joint with a LS gasket, not showing the SR gasket

A standard new gasket, Figure 5a is connected to a ring of wire mesh, Figure 5b. Figure 5c shows a gasket thickness ~ 1/8 inch, and the attached wire mesh ~ 1/2 inch. The wire-mesh ring is secured to a skirt, Figure 5d, which makes the arrangement look like a lampshade and is made of a 1/32-inch thick stainless steel and coated with Corlar epoxy [10]. The skirt helps a crane operator center the LS gasket assembly (LGA) when it is placed onto a pipe nozzle, like the one shown in Figure 5e. That is, once a HC is opened to expose a pipe nozzle, the new LGA could be lowered onto the nozzle. The surrounding skirt would fit on top of the beveled surface of the nozzle to help to locate and center the gasket. Once the new gasket is in place, the HC, containing the old gasket, would be lowered onto the nozzle surface containing the LGA. The combination of the old and new gasket would be then compressed together[2] in the HC to seal the joint to prevent further leaks.

[2] The joining of two gaskets together is not standard H-Canyon operation because it is not currently acceptable per ASME B31.3 Process Piping code but is being researched as a viable method to seal Hanford Connectors remotely.

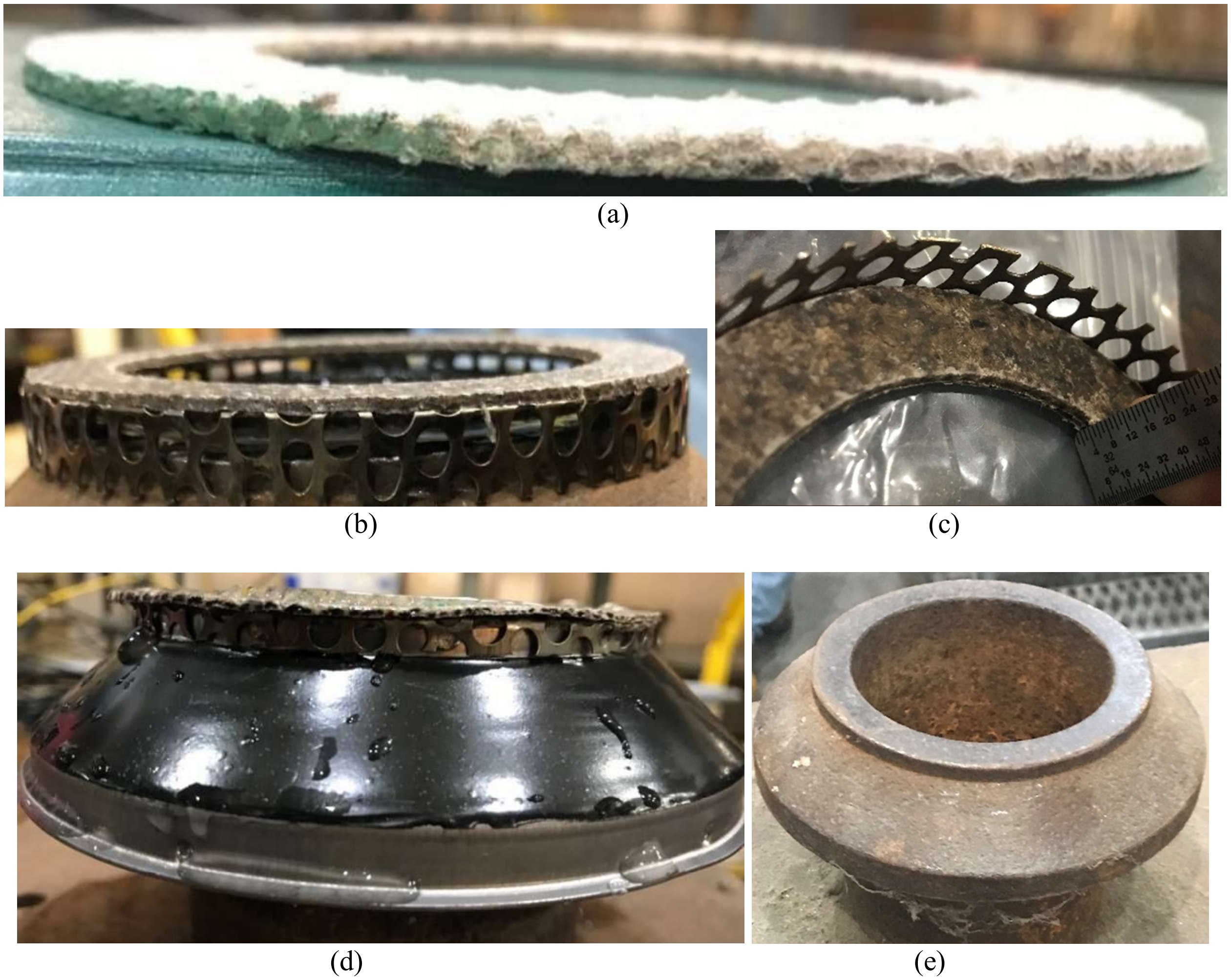

Figure 5: LS gasket assembly:(a) gasket, (b) gasket and wire mesh, (c) gasket and mesh height measurement, (d) gasket and wire mesh connected to steel skirt on a pipe nozzle, and (c) nozzle without gasket

2.0 Experimental Setup

2.1 Gaskets Tested

The general plan for the tests documented in this report was to apply a torque to a mock HC containing a series of gasket arrangements to seal the connection and then measure the load as the torque drops with time as the gaskets relax. When a HC is initially installed it contains a flat gasket held in place with a metal snap ring as shown in Figure 3. As long as a joint stays leak free, that arrangement remains. However, if a leak is perceived and cannot be stopped with further tightening of the installed seal, then a possible solution may be the placement of a LS gasket. Due to the downtime needed and personnel risk to replace an SR gasket, another method to stop the leak would be preferred. As previously discussed, a possible solution would be to open a HC to install an LS gasket, which could be placed remotely on the nozzle so that when the HC connection is again closed, the LS gasket is pressed against the leaking SR gasket. When torque is applied to the HC the two gaskets press together to seal the leak. Several gaskets and arrangements were tested. An excellent description of gaskets used for Hanford Connectors can be found in Section 10.8.4 of reference [2]. The designs and materials in use can be found in references [10-14], but the current gaskets utilized are from the American Braiding Company and are made from white asbestos fiber intertwined with 304 stainless steel strands and impregnated with Teflon. **Table 1** lists the gaskets included in the current test.

Table 1. Gaskets Tested

Gasket	Test Reference Name	Type	Nominal (2) Thickness (inch)
4-Hole Special	4-Hole	American Braiding	0.105
Snap Ring	SR	American Braiding 340-S	0.105
Old Style Lampshade	LS-o	Manville MX 4196	0.120
New Style Lampshade	LS-n	American Braiding	0.150
Double Gasket (1)	DG	American Braiding	0.185

Notes:
(1) DG was used for some tests because manufacturer did not have a sufficient number LS gaskets to test.
(2) Thickness tolerance was specified to be ±0.015 inch.

Each test is generally distinguished by a different gasket arrangement and an initial torque value. For most gasket test arrangements an initial torque is applied to the HC, which is then subsequently retorqued after a period of gasket relaxation. However, there were variations to this, but all gasket arrangements and the type of torque applied are listed in **Table 2**.

Table 2. Gasket Arrangement and Ambient Temperature During Each Test

Test	# of Gaskets	Gasket 1	Gasket 2	Type Torque
1A	1	4-Hole	none	Initial
1B	1	same	none	Retorque
2A	1	SR (1)	none	Initial
2B	1	same	none	Retorque
3A	1	LS-o (2)	none	Initial
3B	1	same	none	Retorque
4A	1	SR	none	Initial
4B	1	same	none	Retorque
5	1	SR	none	Initial
6A	1	SR	none	Initial
6B	1	same	none	Retorque
6C	1	same	none	Retorque
7	1	LS-n (3)	none	Initial
8A	1	LS-n	none	Initial
8B	1	same	none	Retorque
8C	1	same	none	Retorque
9A	2	SR	LS-n	Initial
9B	2	same	same	Retorque
9C	2	same	fresh LS-n	Initial
10A	1	SR	none	Initial
10B	1	same	none	Retorque
10C	2	same	LS-n	Initial
10D	2	same	same	Retorque
11A	1	SR	none	Initial
11B	1	same	none	Retorque
11C	1	same	none	Retorque
11D	2	same	LS-o	Initial
11E	2	same	same	Retorque
11F	2	same	same	Retorque
12A	1	SR	none	Initial
12B	1	same	none	Retorque
12C	1	same	none	Retorque
12D	1	same	none	Retorque
12E	2	same (4)	DG (5)	Initial
12F	2	same (4)	same	Retorque
13A	1	SR	none	Initial
13B	1	same	none	Retorque
13C	2	same	DG	Initial
13D	2	same	same	Retorque
13E	2	same	same	Retorque

(1) SR = Snap Ring Gasket (0.105" thick)
(2) LS-o = Lamp Shade Gasket (old style 0.120" thick)
(3) LS-n = Lamp Shade Gasket (new style, 0.150" thick)
(4) SR from 12D remained but metal ring was removed
(5) DG = Double Gasket (0.190" thick)

The initial Test Series, i.e., 1 through 8, tested individual gaskets. Test 1 only used a special gasket, i.e., a single 4-hole gasket, Test Series 2, 4, 5, and 6 only used a single SR gasket, and Test Series 3, 7, and 8 only used a single LS gasket. For the latter tests, i.e., 9 through 13, the number of gaskets increased from one to two, or even three if the non-standard double-layered gasket (DG), of Test Series 12 and 13. A DG can be considered two gaskets because a DG was two gaskets glued together to represent a single LS gasket. For these later tests the installed SR gasket from the preceding sub-test was generally not replaced, so the new initial torque was a retorquing of the SR gasket that remained. This was performed several times because it is like the situation that is desired to fix a leak in HCA jumper gasket connections. That is, the replacement of an installed SR gasket is not desired because of the time needed and personnel risk involved. Therefore, the SR gasket would not be replaced but rather a LS gasket would be added, so the old gasket would be merged with the new LS gasket.

2.2 Method of Testing

The general method was to set up a mock HC with a desired gasket arrangement and then apply an initial torque. In general, an approximate 700 ft-lbf torque was applied with a torque wrench on the ACME screw shown in the left photograph in **Figure 6**. The computer output is adjusted so that its reading matched the torque-wrench value by adjusting the Torque Divisor (TD) factor. This factor converted force to torque, based on the readout of the calibrated torque wrench, with the force measurements that came from the calibrated strain gauges located on each of the three HC jaws. See Appendix B for an explanation of the strain gauge calibration and measurement.

Figure 6: Photograph of the mock Hanford Connector mounted at the test location

Once the torque was set, a test began. The force, converted to torque, was then monitored over time until the end of a specific period. As listed in **Table 2**, each test series included several tests, depending on the gasket arrangement. For example, Test Series 10 started with Test 10A, which used a SR gasket. After the test period for Test 10A, Test 10B started by retorquing the SR gasket from Test 10A. At the end of the test period for 10B the connection for HC was opened and a fresh lamp-shade gasket, LS-n, was installed on the pipe nozzle, but without removing the SR gasket used in Tests 10A and 10B. The HC was closed, and a torque was applied to started Test 10C. Finally, at the end of test period for Test 10C the HC was retorqued to begin Test 10D. At the end of the test period for 10D, Test Series 10 was terminated. To simulate the HCA pipe system pressure, with the HC closed and torqued to the initial value, the internal cavity of the mock HC on the nozzle was filled with water and pressurized to approximately 150 psig. The right photograph in **Figure 6** shows the piping that permitted the nozzle cavity to be filled with water and pressurized. The pressure was set to 150 psig because it is the maximum HCA service pressure [2]. A detailed step-by-step list of the test method is given in the following section.

2.3 Test Steps

1. Install a gasket arrangement, as listed in **Table 2** either:
   a. A SR gasket, which was held in place on the connector block by a metal snap ring, or
   b. One of the gaskets referred to as a LS gasket
      i. New style (LS-n), (0.150” thick)
      ii. Old style, LS-o (0.120” thick)
      iii. Double gasket, DG (0.190” thick), which was used when none of the standard LS gaskets were available.

   These LS gaskets were simply placed on top of the mock pipe nozzle ready to receive the HC.
2. The HC was installed by hand onto the nozzle.
3. Before applying a load to the HC, the strain gauges were zeroed. This was achieved by adjusting the initial voltage value (in microvolts) in National Instruments™ Measurement Explorer for each channel of the signal processing equipment to set the readings to zero. To equate the measured loading in the jaws (using the strain gauges) to the torque applied, the computer (See Appendix B) was programmed to add all three-jaw axial loading forces, and divide that summation by a calibration value, termed the Torque Divisor (TD) in the LabVIEW™ Virtual Instrument. This TD then related the jaw loading (in lbf which was calibrated as part of the test set up) to the torque (in ft-lbf) indicated on the torque wrench.
4. Apply torque using the calibrated torque wrench described in Appendix B. With the calibrated torque wrench, loading was applied at 300, 500, and 700 ft-lbf. At each loading, a TD was iterated to match the computer recorded torque to the calibrated torque wrench, and these values were recorded in the lab book.
5. With the sealed HC equipment, the small existing cavity from the HC block to the bottom of the nozzle plate was filled with water.
6. With the use of a hand-operated hydraulic pump the water was pressurized to approximately 150 psig (this value is the maximum pressure of a typical steam jet jumper [2]). The value of this pressure was recorded by the computer. This internal pressure was employed to have the HC joint in a similar hydraulic environment that exists in the plant where the piping system is always under varying pressures during operation that motivates liquids to move.
7. With an initial applied torque to the HC and the water pressurized, the computer was then programmed to store data at a frequency dictated by the PI and the test started.
8. Each test was allowed to run until sufficient data were recorded to meet the test matrix requirements.
9. Test End

2.4 Measure and Test Equipment

To measure the operation of the HC mockup the following measurement equipment was used.

Table 3. Measurement Equipment (1)

M&TE Number	Instrument					Calibration Date	Pre-Test Uncertainty	Comment
	Name	MFG	Model	Range	Tolerance			
51233	P1	Rosemount	1144G0600A22M1	0-200 PSIG	±0.5% FS	5/10/2021	±0.5% FS	Measure Pressure of HC Cavity
51074	TC1	Omega	HKSS-116U-12	0-100°C	+/-2.2°C	3/9/2021	±2.2°C	Measure Atmospheric Temperature
N/A	Strain0	Micro Measurements	CEA-06-250UTA-350	0-3% Elongation	±2.01% RDG	3/16/2021		Measure Jaw Strain
N/A	Strain1	Micro Measurements	CEA-06-250UTA-350	0-3% Elongation	±2.01% RDG	3/16/2021		Measure Jaw Strain
N/A	Strain2	Micro Measurements	CEA-06-250UTA-350	0-3% Elongation	±2.01% RDG	3/16/2021		Measure Jaw Strain
N/A	Strain3	Micro Measurements	CEA-06-250UTA-350	0-3% Elongation	±2.01% RDG	3/16/2021		Measure Jaw Strain
CDS901A	Torque Wrench	Snap On Tool	TE1503FU	300-1500 Ft. Lbs.	±2% RDG	4/26/2021	±2% RDG	To apply initial HC Torque

(1) Details of the measurement test equipment are found in Appendix B

2.5 Data Acquisition System

The computer used to record the measurement equipment was a Dell™ OptiPlex 390 running Windows™ XP and the processing hardware were:

- National Instruments™ Hardware
- cDAQ-9174, signal processing chassis for C-Series Signal Modules
- NI-9213, C-Series Temperature Input Module
- NI-9205, C-Series Voltage Input Module
- NI-9237, Bridge Completion Module
- NI-9949, Terminal Block to RJ50 Connectors
- Micro-Measurements 4 Conductor Wire, PN 430-DFV

An example of the monitoring of one test is shown in a photograph of a moment in time from the front panel of the DAS is shown in **Figure 7**. Specifically, shown are data on the last day, on the14th day of testing, from Test 6C. During this test the applied torque dropped to 507.5 ft-lbf from the initial torque of 699 ft-lbf set on 19th of July. Note the test ambient temperature in the test room was 27.3°C (~81°F). This temperature is not surprising for the end of the mid-summer's day.

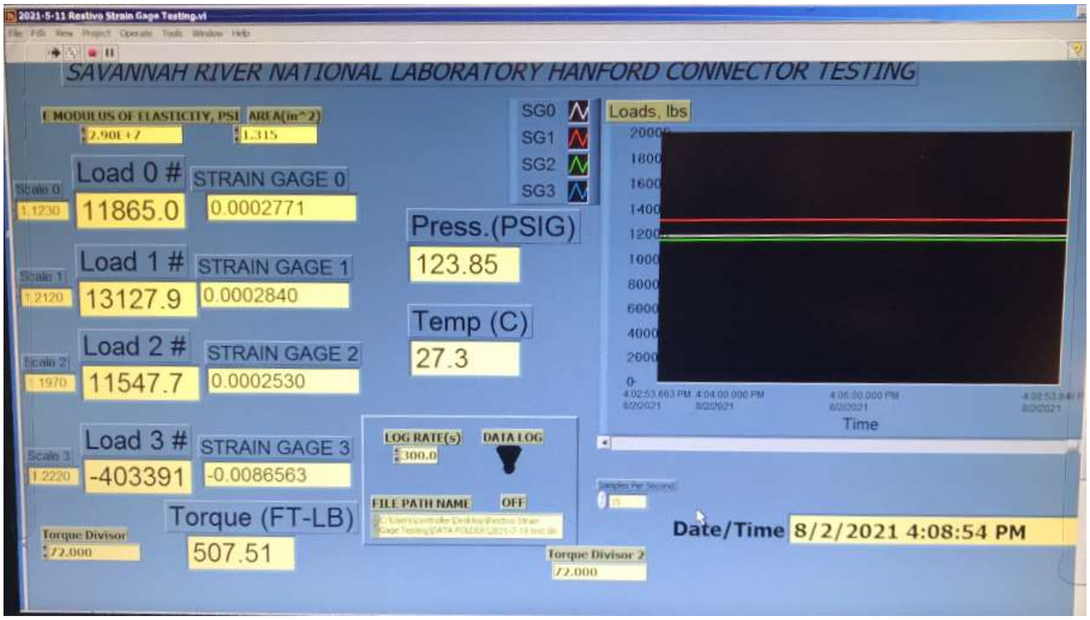

Figure 7: Data Acquisition System Front Panel

3.0 Results and Discussion

For the test campaign, which lasted from May 2021 to January 2022, the measured torque and force data are listed in Appendix A, at indicated time intervals. The converted torques from the measured total forces to the HC are listed in Table 6 through Table 11. The measured forces to the HC are listed in Table 12 through Table 17. All other data, e.g., temperature, pressure, individual forces, TD applied, as well as at all time intervals recorded are listed in the complete set of spreadsheets found in the SRNL Electronic Notebook (ELN) [15].

The required data are the load (force) applied to the mock HC to show how that load changes with time as installed gaskets relax (or creep). The method of tightening to a known value is by utilizing a calibrated torque wrench. However, torque is not force, but a method of applying a force. The relationship between torque and force is complex [16-18]; which involves the mechanical properties of the materials, the design and age of the screw, friction, etc. For an HC it is even more complex due to the fact it is not a bolt tightening down on a washer but a screw pulling up on a nut that pulls up on three hooks, or jaws, that pull up on a nozzle, which forces the nozzle onto the HC block surface that contains the gasket to seal the connection. Therefore, force was measured directly by instrumenting the HC jaws with strain gauges [19] checked against a calibrated tensile tester, as explained in Appendix B. However, for convenience, the applied loads and the change of those loads are given in terms of torque, which is based on the total force applied, which is the sum of the forces measured from each of the three HC jaws. For each test, the calibrated torque value, and the resulting calibrated force values, were used to develop the conversion factor, TD, such that once an initial torque was applied to set the initial applied force, then that force and its subsequent changes, as a gasket relaxed, is given in terms of torque. That is, the data of applied and changing loads are given in terms of either torque or percentage of changing loads relative to the initial load. For example, if the initial applied load in terms of torque was 700 ft-lbf, which subsequently drops to 312 ft-lbf, then that would be represented as a reduction of 312/700 x 100% = 45%. The following chapters of this Results Section highlight important aspects of those and other data to better understand the results.

3.1 Pressure and Temperature

As already discussed, the HC mockup was pressurized to represent the system pressure in the HCA piping system. However, the small size of the test equipment provides an internal volume of approximately 90 in^3, or just under ½ gallon. This volume included the volume of the nozzle cylinder and the piping that supplied the water up to the shut-off valves. The internal volume of the pipes was on the same order of the volume within the nozzle cylinder enclosed by the HC. The HC and piping that fed and pressurized the water is shown in **Figure 8**.

The pressure measurements are not shown for all the tests because they are all similar to that experienced from Test 5, which is shown as an example, **Figure 9**. In the graphs the pressure history of Test 5 is shown over its 360-hour test period, or 15 days. Most of the drop in pressure occurs early, **Figure 10**. From an initial pressure of 150 psig, it dropped about 30 psi after 24 hours, and to around 95 psig by end of that test period. However, 35% of the lost pressure occurs during the first 8 hours. While leaks were not noticed, the hydraulic system was not tested for leak tightness. There were several valves, a plastic feed tube, a hand pump, and each time the HC was removed the piping unions had to be disconnected; therefore, a leak is assumed to have caused the pressure drops. The pressure loss was consistent and for the small volume of water used any small leak would lead to a significant pressure drop. Furthermore, experiencing most of the pressure loss early, when the pressure was the highest, makes sense when the potential to leak is the greatest.

Figure 8: Piping connected to Hanford Connector to Supply Internal Pressure

Figure 9 only shows data at infrequent intervals, but the pressure was monitored very frequently, and exhibited considerable fluctuation that corresponded to the changes of the ambient temperature. Because the test volume is very small, which is not prototypic of the very large volume of the actual HCA pipe system, its reaction to the environmental temperature was noticeable. The ambient temperature changes were on the order of ±5°C. This was enhanced because the test system had to contain many pockets of air, which accumulated in the many small spaces in the pipes and nozzle. Note that the HCA system could have a maximum pressure of 150 psig [2], but the working pressure is generally much smaller, but more importantly its volume is several orders of magnitude larger, which would dampen such fluctuations.

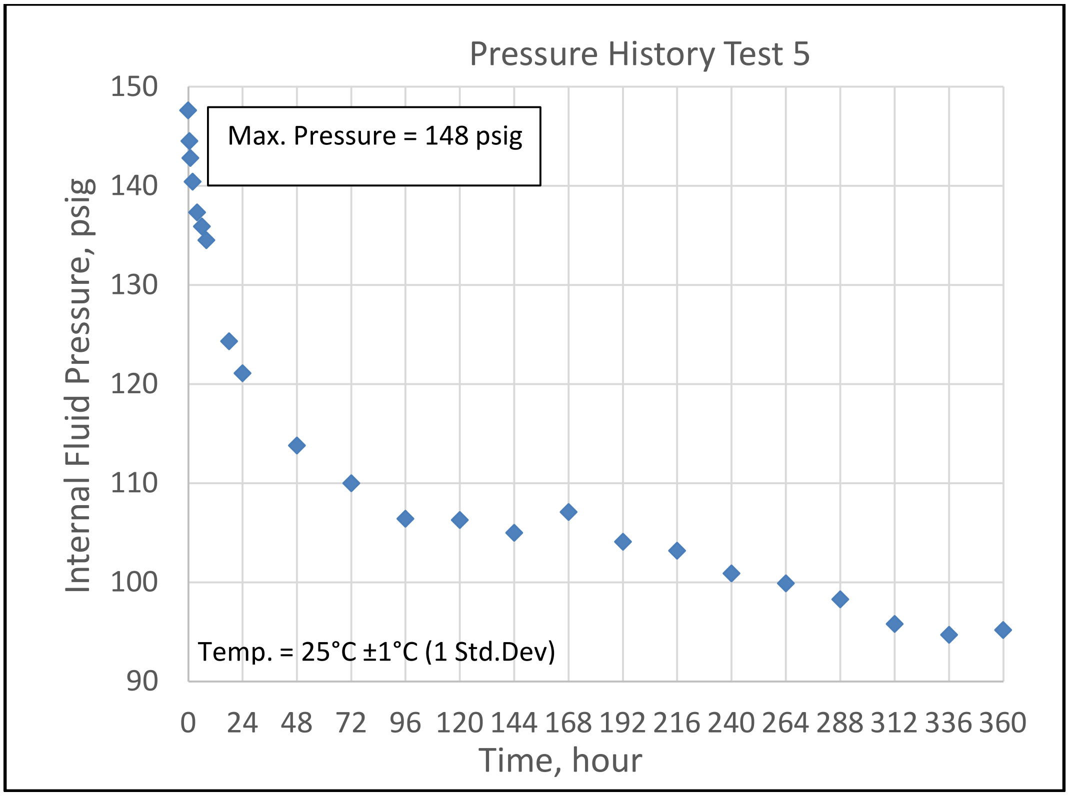

Figure 9: Change of Internal Water Pressure during Test 5

Besides pressure fluctuations, the applied pressure also causes an opposing force that counters the force applied to the gaskets by the HC jaws, but it should be insignificant. For the specific test setup, a 3-inch HC was used. The surface on which sits the gasket has a 3-inch opening, which has an area of approximate 7.07 in^2. Therefore, an applied 150 psig creates an opposing force of 1060 lbf. From the mechanical torque to the HC the applied force is approximately 18,000 lbf for each of the three HC jaws, which was measured as part of the test. That leads to a total opposing force of approximately 54,000 lbf. Therefore, the force from the water was less than 2% of the force produced from the HC jaws. While the opposing force from the water is insignificant to the force that seals a nozzle to the HC block, this small force may be one reason the applied torque never seemed to stop dropping, even after weeks, which is discussed in the next section.

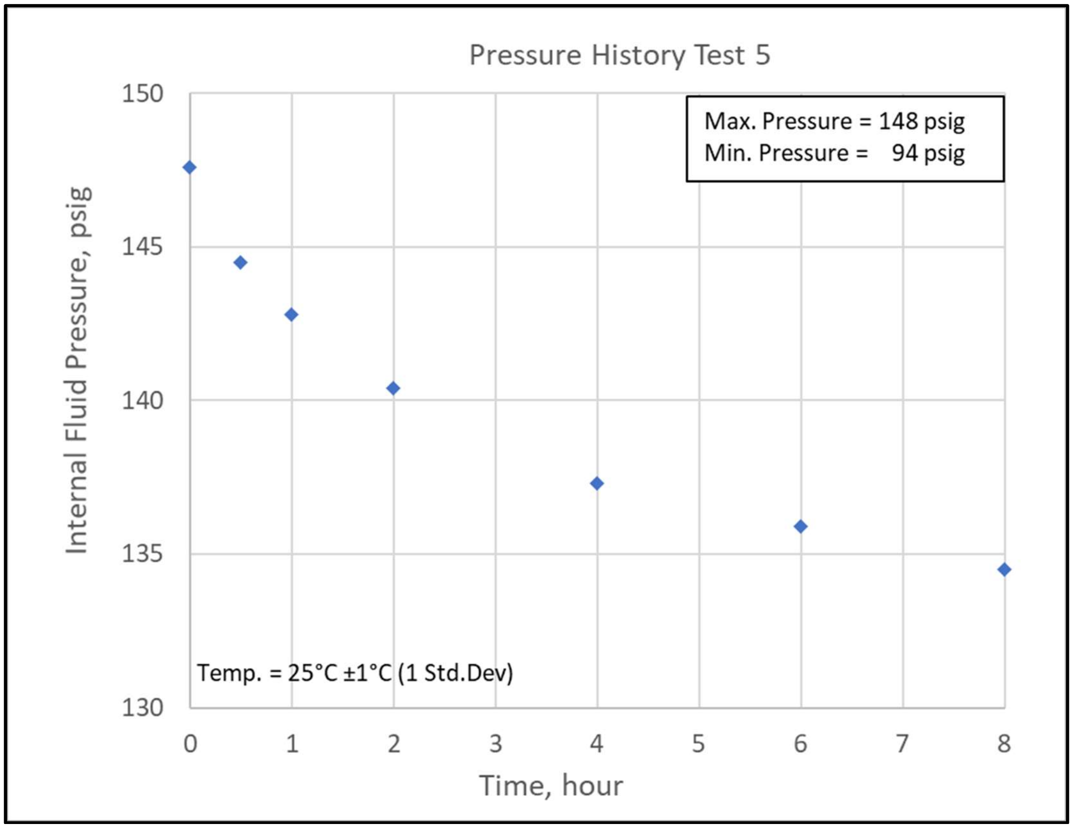

Figure 10: Early changes of Internal Water Pressure during Test 5

3.2 <u>Gasket Relaxation</u>

One result that was seen in most of the tests was that after applying a torque to the HC, the force began to drop immediately and continued to drop, even after 2 weeks, as shown in **Figure 11**. After 23 days of Test 7 and 15 days of Test 5 the reduction in torque slowed considerably; however, the reduction never fully stopped. The amount was very small, which is not easily seen in the figure. This effect can be seen better by looking the trendline from the last 2 of 15 days of the Test 5, **Figure 12**. Extrapolating the trend line on the graph predicts that the torque would reach 500 ft-lbf after approximately 3 months. However, the slope of the trend may become even less with time, so the timeline is probably further into the future. The observed fluctuations in torque will be explained in more detail later, but they occur due to effects of temperature changes on the small, pressurized volume within the HC and nozzle test setup. That is, as the ambient temperature fluctuates throughout the day it affects the temperature, and thus the pressure and applied force, of the test setup. Note that the time between a peak and valley shown in **Figure 12** is approximately 12 hours during which the temperature changes from cooler in the morning to hotter in the evening.

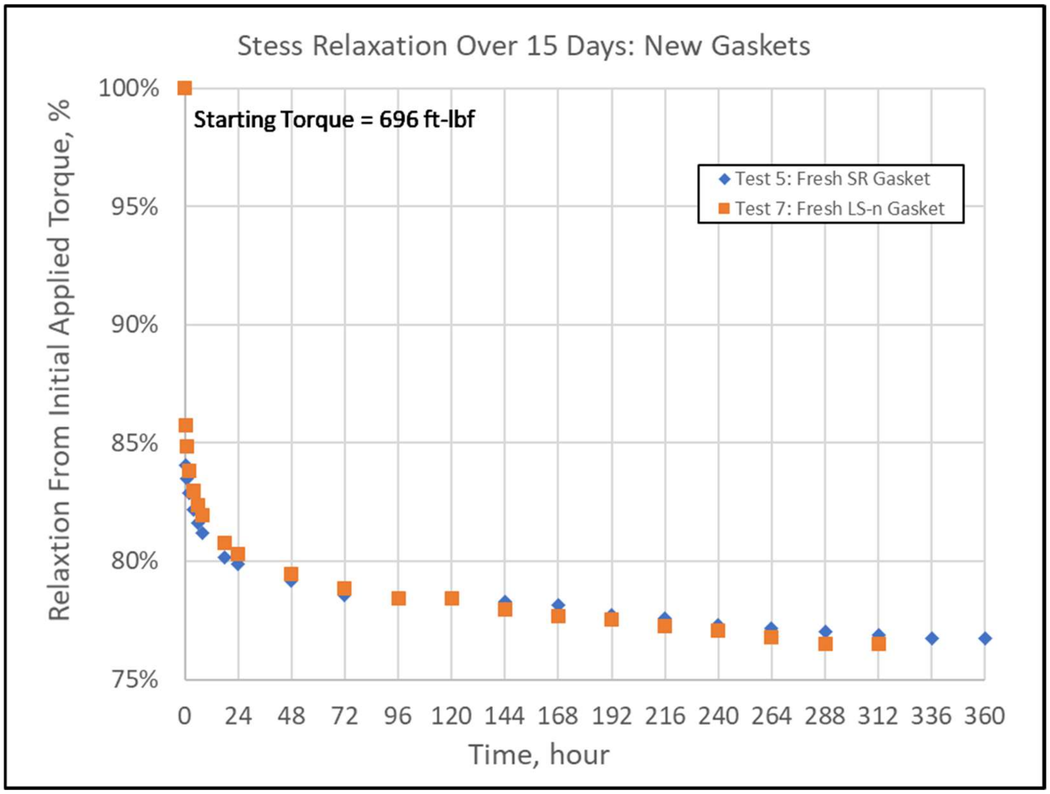

Figure 11: Change in applied torque to fresh SR and LS-n gaskets

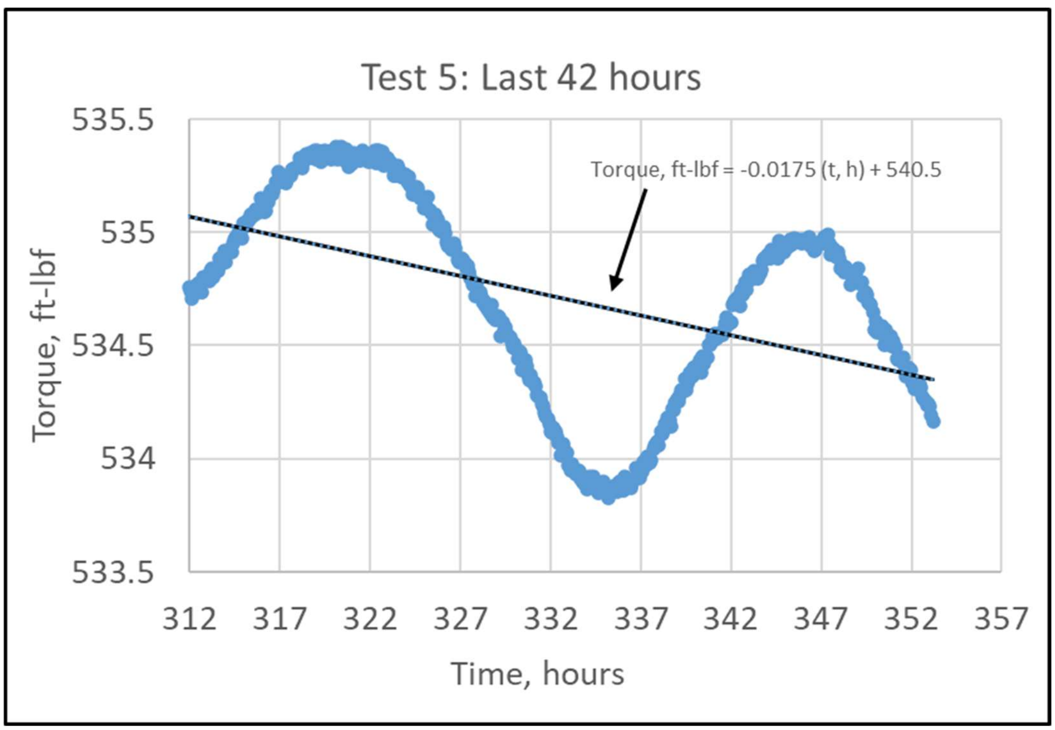

Figure 12: Dropping torque at end of Test 5

Figure 11 and **Figure 13** show two different gasket types that were tested separately, that is, a SR gasket and the thicker LS-n gasket. The material of both gaskets is the same asbestos-Teflon material, but the SR gasket has a nominal thickness of 0.105 inch, while the LS-n gasket is thicker at 0.150 inch. It appears these differences in thickness did not have significant effect because the trend in the drop of applied torque appears to be the same. From **Figure 11** the two trends not only overlap, but they switch on which had the lower drop after about a week. However, the difference is within measurement uncertainty.

There was a large reduction from the initially applied torque over the first few hours and days, but then the torque reduction slowed dramatically. The sharp drop during the first few hours is most likely due to the gasket material relaxing, as it cold flows from the applied pressure on the sealing surfaces. Over the 15 days the applied torque dropped to 77% of the initial values of 696 ft-lbf. However, it is important to note 60% of that drop occurred in the first 30 minutes, **Figure 13**. In fact, when considering all the test data, the loss of torque happens almost immediately, which literature shows is a common occurrence [7]. For example, see a comparison of data from literature [7], **Figure 14** which shows the relaxation of PTFE Teflon gaskets of similar thickness, i.e., 0.065" and 0.125", with data from Test 5 (SR=0.105-inch thick) and Test 7 (LS gasket =0.150-inch thick). Both data sets are from a similar starting applied force, near 50,000 lbf. The comparison implies that gasket relaxation from two different gasket arrangements is very similar. Finally, **Figure 15** shows that during the first 5 minutes after an initial torque up to 33% is lost, which is more than 50% of what occurs in the first 30 minutes. **Figure 15** also shows that the loss in the initial applied load is less dramatic if a HC is retorqued, but it still could be on the order of up to 8% of the initial load.

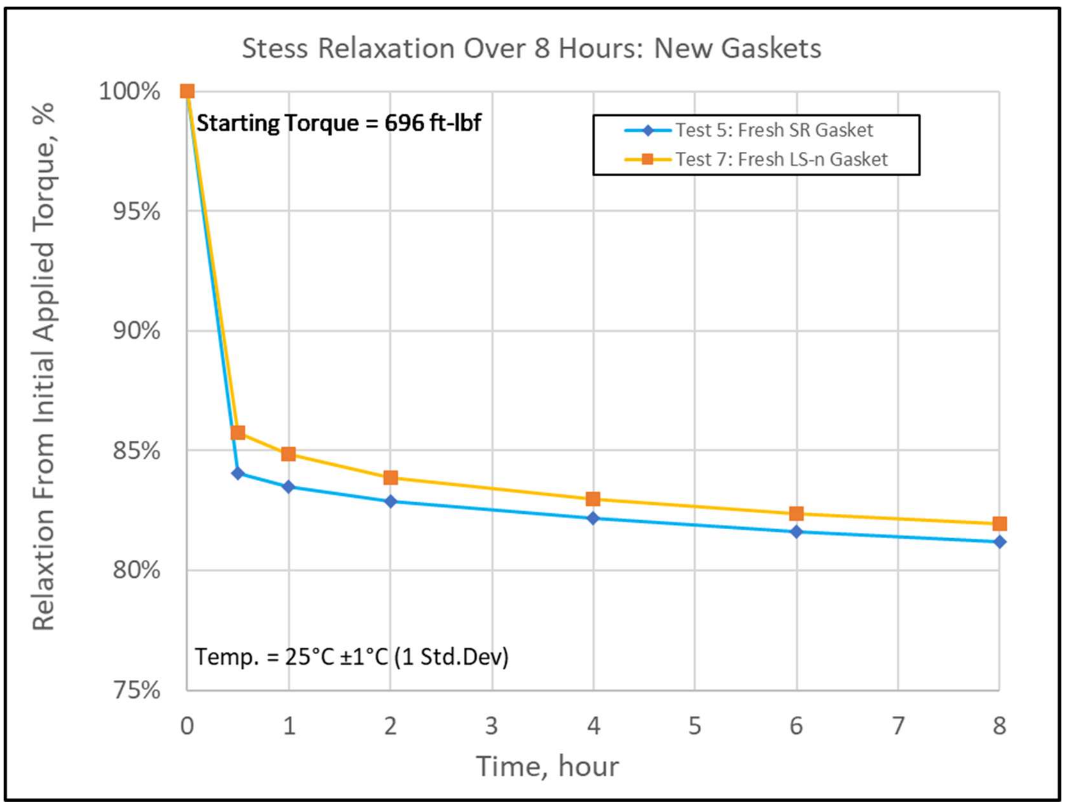

Figure 13: Early changes in applied torque to fresh SR and LS-n gaskets

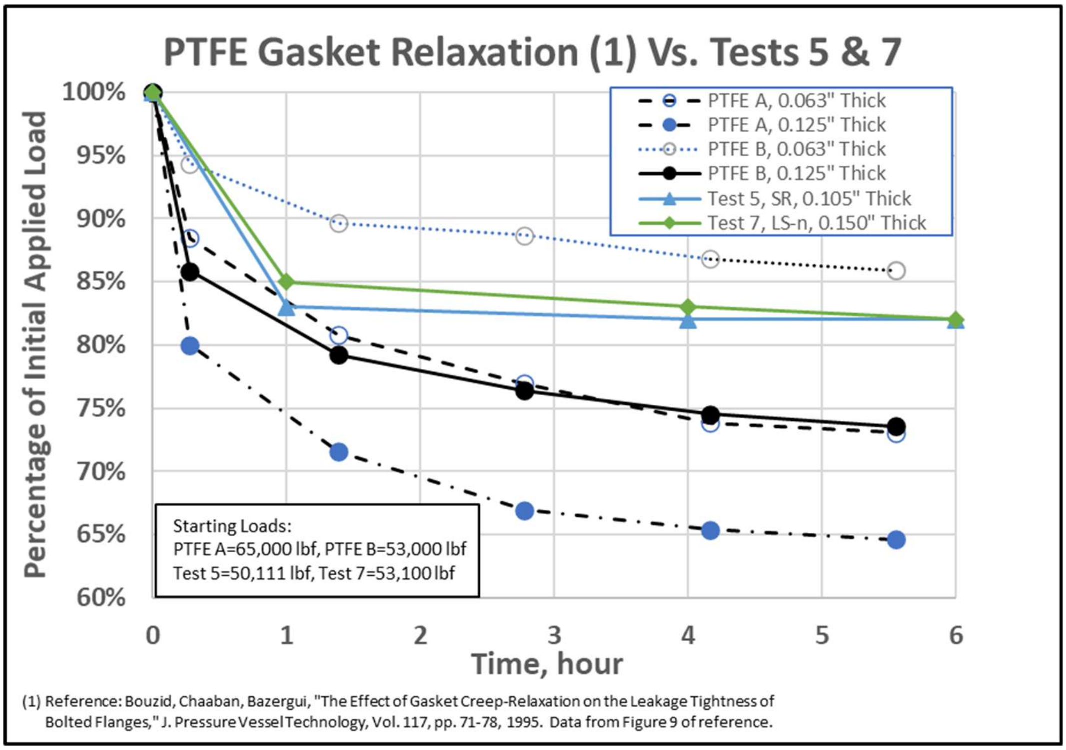

Figure 14: Compare Gasket Relaxation of Gaskets Tested to Teflon Gaskets

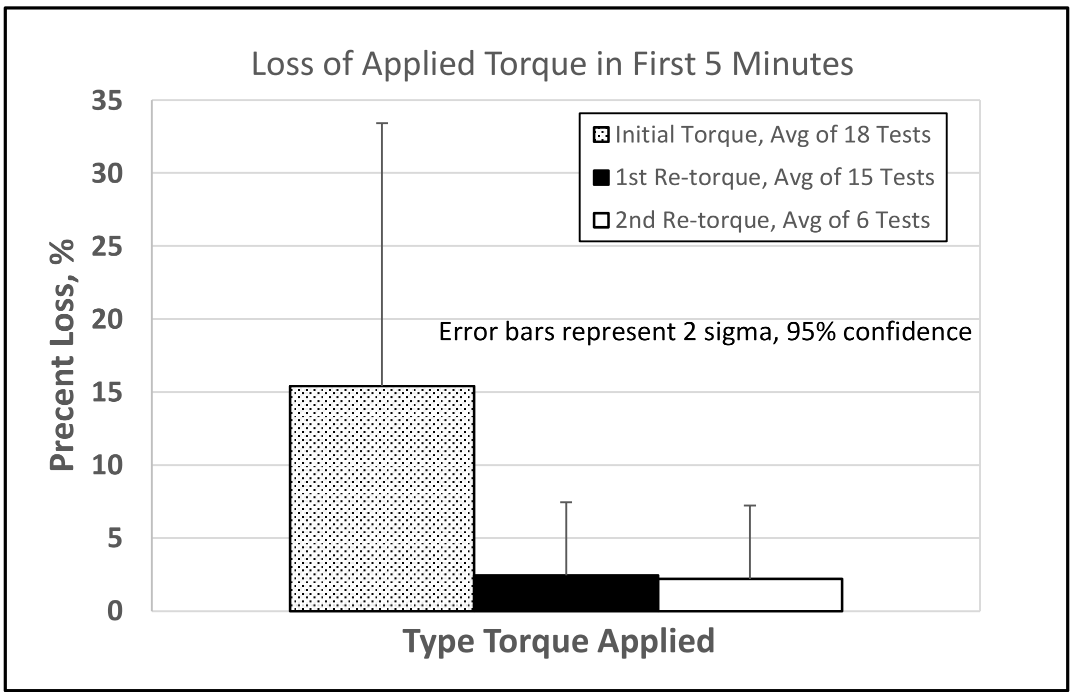

Figure 15: Torque after 5 minutes from the initial application

Another important way to view the data shown in **Figure 11** is by the actual measured change in torque over the approximate 2 weeks of both Tests 5 and 7. Extrapolating the data from Test 7 to match the same period of Test 5 the initial torque dropped from 696 ft-lbf to 520 ft-lbf, which is important. Previous tests [2] were performed to determine when a leak occurs from Hanford Connectors. Those tests showed that at fixed applied torques to the HC, with a 300-psig system pressure, that the water only began leaking from the gasket after the applied torque was 500 ft-lbf or lower, but for a more typical operational pressure of 100 psig no leaks were found at 400 ft-lbf and above. However, a more restrictive requirement is that for post seismic leak tightness it is required for the torque to be at least 312 ft-lbf [8]. **Figure 16** shows that after 2 weeks from the initial application of a 696 ft-lbf torque the HC torque was still above that 500 ft-lbf threshold. As previously discussed, from all the data trends for all the gasket arrangements, the magnitude of the initial torque never seems to stop dropping; however, the rate of drop after two weeks is in fractions of a ft-lbf per day. For example, using the measured torque values from Test 5, which started with a fresh SR gasket, on day 13 it was 535.10 ft-lbf, on day 14 it was 534.31 ft-lbf, and on day 15 it was 534.04 ft-lbf. A very rough extrapolation of those data points predicts the torque threshold of 500 ft-lbf would occur at approximately day 80. Knowing those data contain measurement uncertainty, that the trend is not strictly linear, and using only three points, conservatively it is probably safe to say it would take around 2 months for the 696 ft-lbf to drop to 500 ft-lbf. Furthermore, the leak test was for a system pressure of 300 psig, while the actual operating pressures in HCA piping system are considerably lower and not constant. There are many connectors, so the leaks that do occur in HCA could possibly come from connectors that have been leak tight for several months, or longer. It is not known if observed leaks in HCA emanate from connectors that had been seal for more than two months [5], but this could be checked.

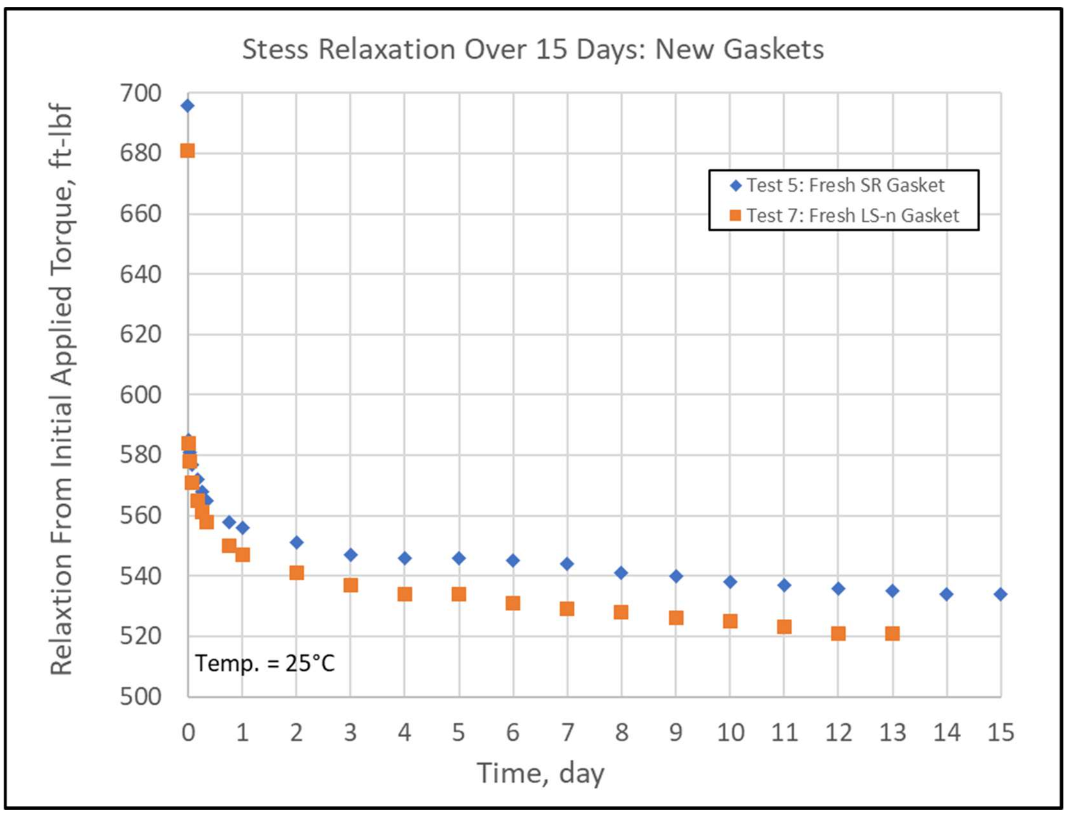

Figure 16: Changes in applied torque to fresh SR and LS gaskets

3.3 Gasket Relaxation for Fresh SR Gaskets

Despite the similar drops in initial torques seen in **Figure 11**, considerable variation in torque reduction was observed on repeated applications to similar gaskets. **Figure 17** depicts the results of eight different tests that all started with fresh SR-type gaskets. The reduction in applied torque varied considerably on the first day of testing for each with a drop to between 90% and 60% of the initial applied torque, which is listed in the legend. Some of the variation may have been due to the test mounting, pressure, and applied torque, but there is no clear trend. The best that could be concluded is that after 1 day the applied torque to a new SR gasket will drop to approximately 75% of its initial torque. Assuming that the initial torque is 700 ft-lbf that means it will drop to approximately 525 ft-lbf and on an individual bases a few of the tests are at or below 500 ft-lbf. This is important because leaks were found to occur below a torque of 500 ft-lbf [2], which implies that a further loss in the sealing force may lead to a leak. Equally important is to recognize that most of the loss of applied torque appears to occur during the 30 minutes after a torque is applied, **Figure 18**. The drop and recovery seen during Test 2A, **Figure 17**, during the first few hours is unexplained. The next section investigates if a follow-up retorque is beneficial to an installed SR gasket.

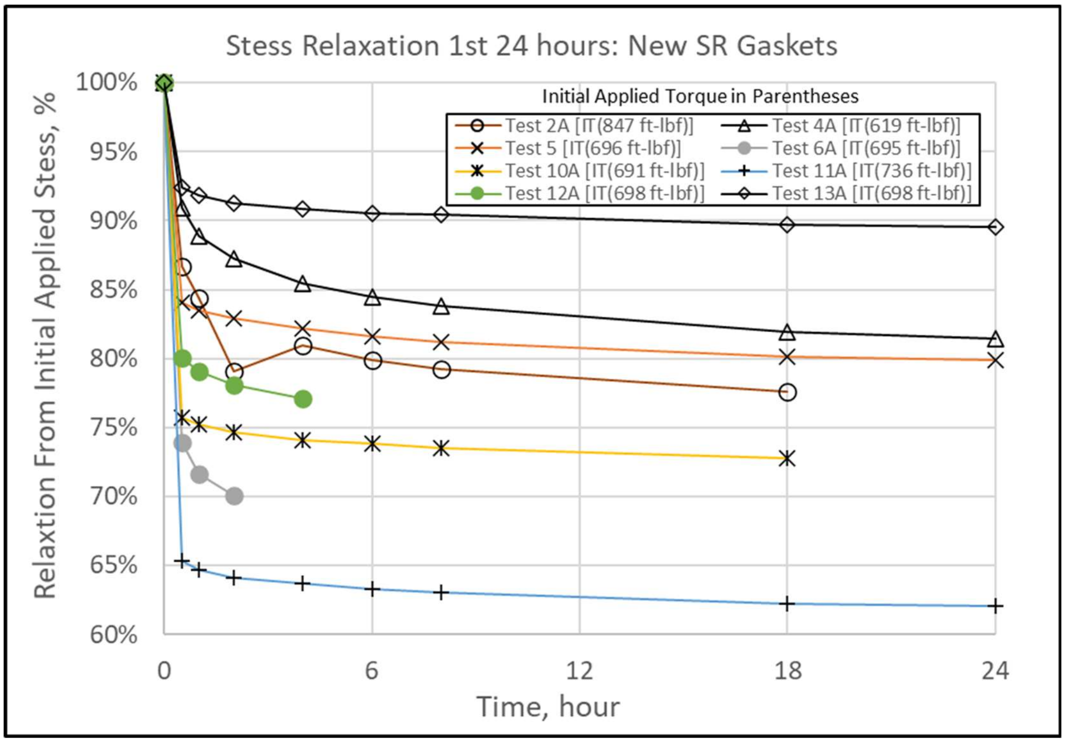

Figure 17: Changes in applied torque to several fresh SR gaskets

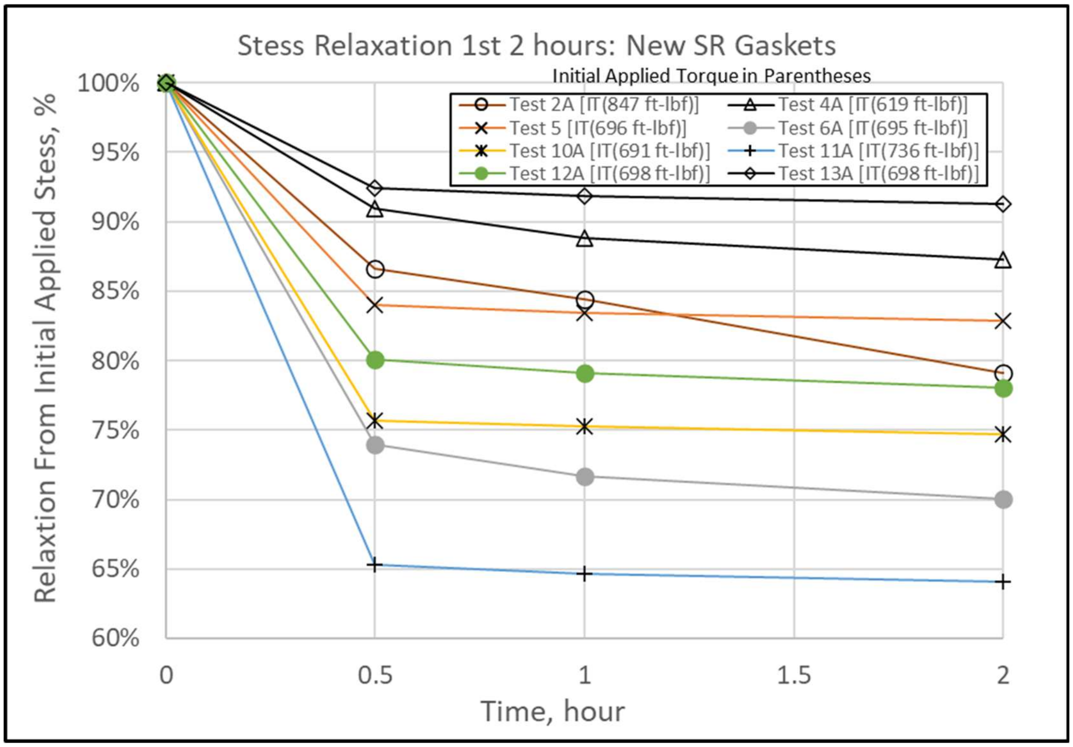

Figure 18: Early changes in applied torque to several fresh SR gaskets

3.4 Gasket Relaxation after Retorque SR gasket

Of the 8 tests shown in **Figure 17** that started with fresh SR gaskets, 7 tests were followed by retorquing those same gaskets after those tests were completed. **Figure 19** shows the results of the first 24 hours after the HC was re-torqued to approximately 700 ft-lbf. Two aspects are immediately obvious. The spread of the drops in the initial torque is much less, i.e., a spread of 92%-62% to spread of 98%-80%. Test 6B ended at 4 hours, so it is not known what drop in applied torque it would have represented. However, it appears that retorquing a fresh SR gasket results in considerably less loss from the initial applied torque from an average of 25% to a smaller loss from the initial torque of approximately 10%. This was also seen during the first 5 minutes after a retorque, **Figure 15**. Furthermore, as was evidenced with a fresh gasket, the loss that occurs during 24 hours, primarily happens during the first 2 hours, **Figure 20**, and within those 2 hours the first few minutes are crucial, **Figure 15**.

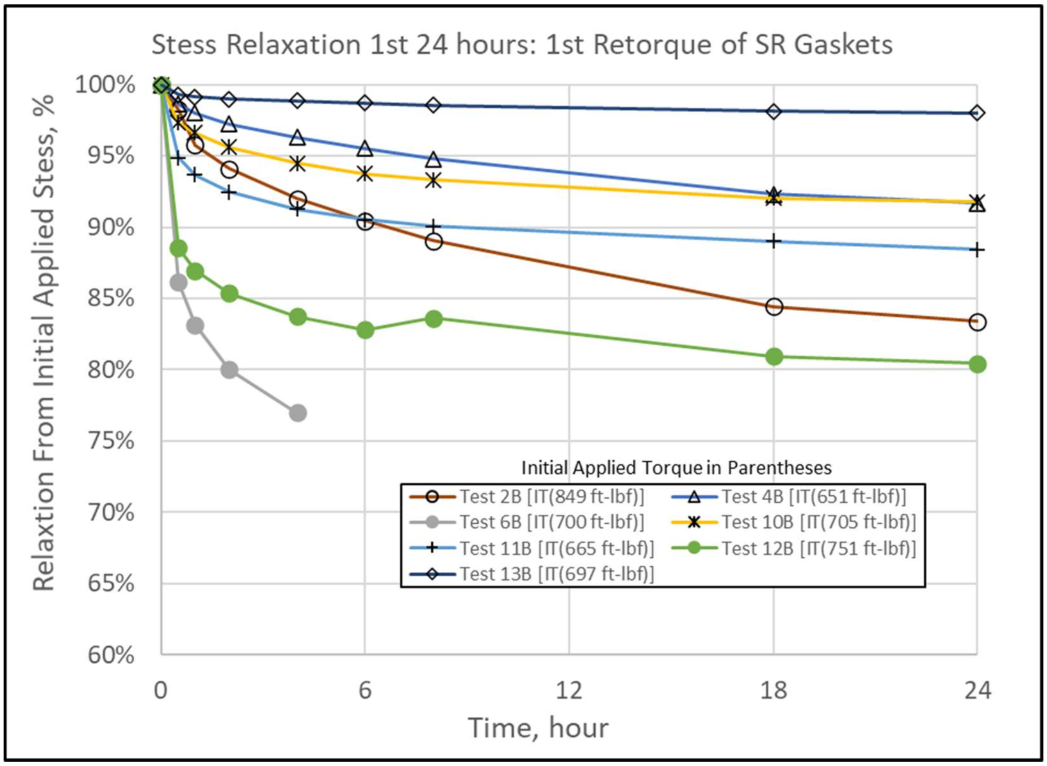

Figure 19: Changes in applied re-torque to several SR gaskets

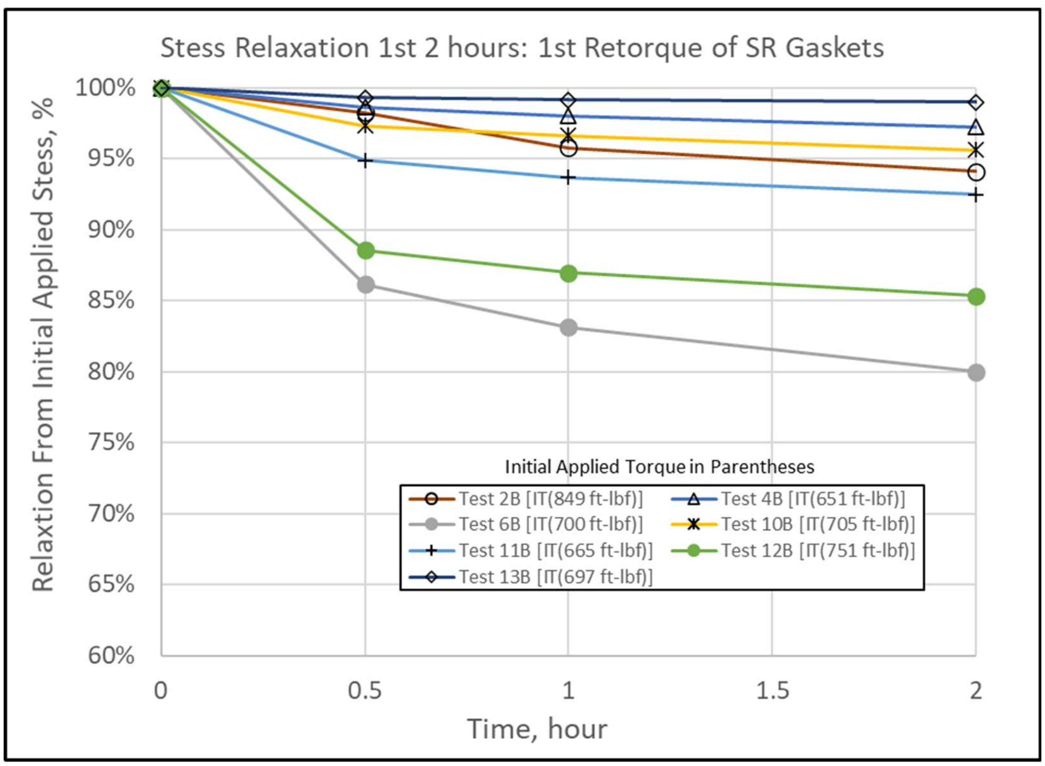

Figure 20: Early change in applied re-torque to several SR gaskets

3.5 Second Retorque of a SR Gasket

Of the 7 tests performed to retorque the SR gaskets 3 were subsequently retorqued for the second time so a comparison could be made on any further benefit from such action. Unfortunately, it appears that further retorquing the gaskets does not result in an improvement beyond what occurred after the initial retorque. As can be seen in **Figure 21** the drop from the initial applied torque resulted in approximately that same loss as observed in the first retorque. The loss may be even a little larger than the first retorque, which may be evidence that the gaskets are stressed to the point of plastic deformation. This was also seen to occur during the first 5 minutes, **Figure 15**.

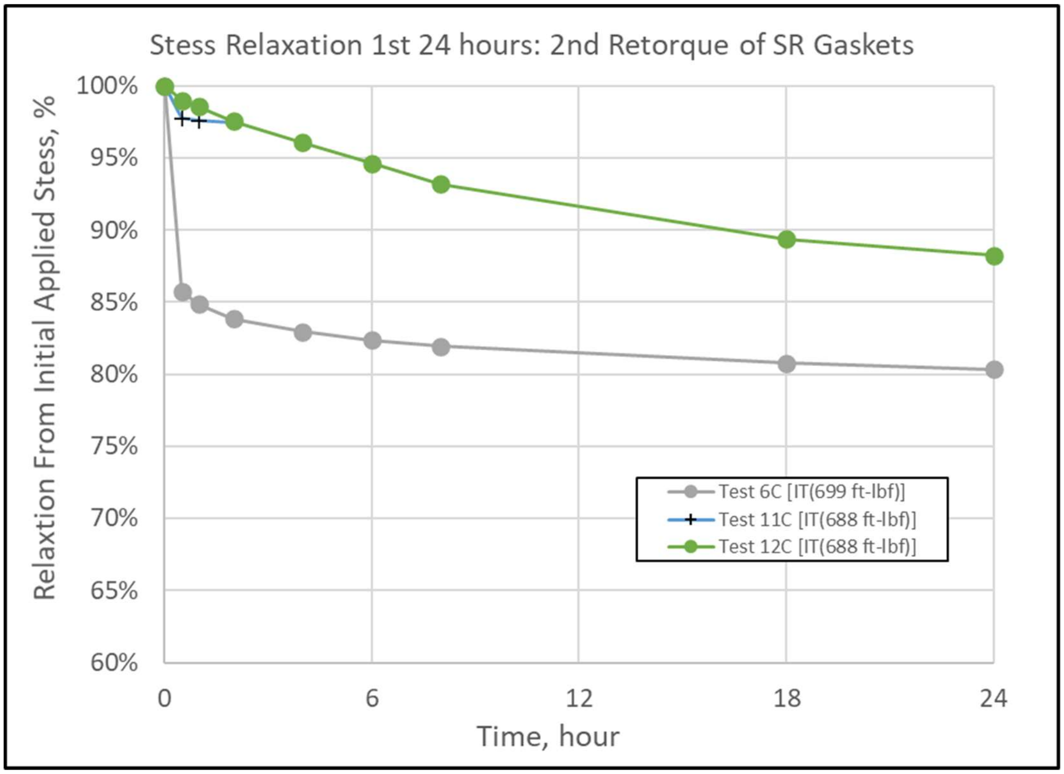

Figure 21: Changes in applied re-torque to several SR gaskets

3.6 Relaxation for Individual 4-Hole and Lamp-Shade Gaskets

Four tests were completed in which no SR gaskets were used but several other types: a special 4-hole gasket, and two different type of LS gaskets, the new type that is 0.150-inch thick (LS-n gasket) and the older type that is 0.120-inch thick (LS-o gasket). As shown in **Figure 22**, over 24 hours the gasket that performed the best, with respect to the loss from the initial applied torque, was the special 4-hole gasket, which was measured to be 0.11-inch thick. The next best was the old-style LS gasket with a thickness of 0.120-inch thick and the poorest performance occurred with the thickest (0.150-inch) LS gasket. This is also depicted in the **Figure 23** that shows the first 2 hours of operation. While this may indicate that thicker gaskets lose more of the applied force as they relax and cold flow; however, more data would be needed to make a conclusion because there are other results that do not follow this trend. For example, Tests 7 and 8A both used fresh new style LS gaskets with the same thickness, but their respective torque histories are significantly different. The reason for the larger difference with the gasket for Test 8A is unknown.

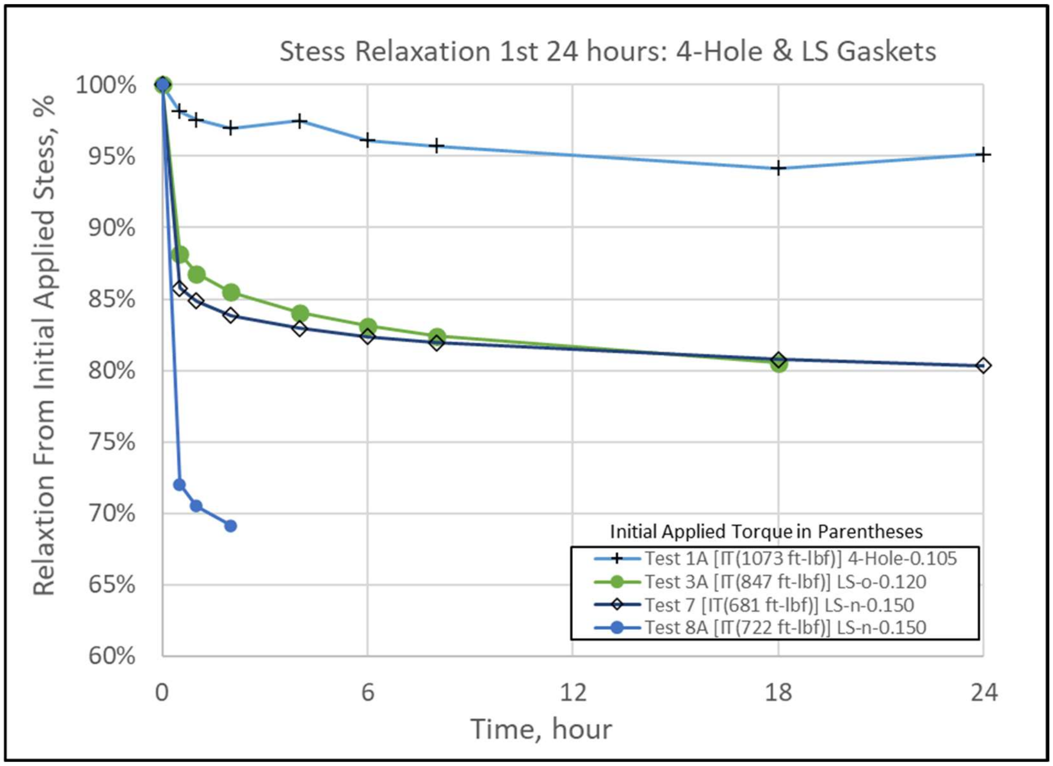

Figure 22: Changes in applied torque to several fresh gaskets, 4-Hole & LS

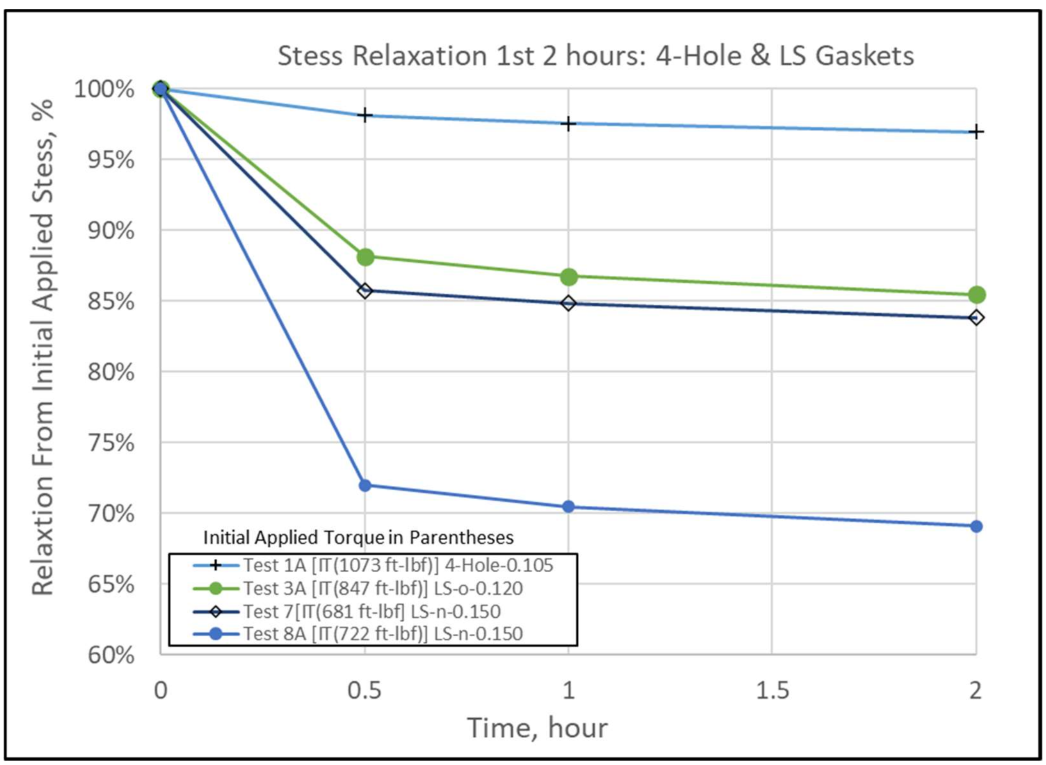

Figure 23: Early changes in applied torque to several fresh gaskets, 4-Hole & LS

It may turn out that such a variation is common from one batch of gaskets to another but without further testing the true reason remains unknown. For tests 3A and 7 both gaskets were of the two different types of LS gaskets, with the old style (0.120-inch thick, Test 3A) and the new type (0.150-inch thick, Test 7) and their torque histories are almost identical so for at least these two gaskets the load responses were the same. Another example can be seen over the 2-week period shown in **Figure 16**. The thinner SR (0.105-inch thick) gasket performed like the thicker LS-o (0.120-inch thick) gasket. From all these results it is clear that if gasket thickness needs to be analyzed for its torque properties further tests would be needed.

3.7 Double-Gasket Operation: LS gasket Added to Existing SR gasket

The principal reason for the overall task [6] was to determine the applied torque reactions, i.e., loss of torque through gasket relaxation, of a single gasket arrangement, which was just discussed. The last arrangement, which is currently not standard operation, is the use of two gaskets. Specifically, when a connection is leaking, and further retorquing does not stop the leak, then a HC is opened but instead of removing the existing SR gasket a fresh LS-type gasket is added. For this situation, when the HC is resealed, the old and the new gaskets would be joined forming two layers of gasket material. That is, instead of performing a time-consuming gasket replacement and an increased risk to personnel, the HC is simply opened to insert a new LS gasket remotely.

The tests documented in this section were to demonstrate situations of a SR gasket being retorqued to arrest a leak, followed by the addition of a LS gasket. The tests performed were not set up to determine if a HC would leak, but only to demonstrate the value of an applied torque and how it changes with time for several different arrangements of gaskets. The order of the following discussions of the test data is what is considered most important to demonstrate the required need.

Test Series 11 would be the best example in that it demonstrates the application of an old-style LS-o gasket (0.120" thick) after retorquing a fresh SR (0.105" thick) gasket two times. This is followed by Test Series 10 that utilized a new-style LS-n gasket (0.150" thick) after retorquing a fresh SR gasket once. The discussion then analyzes Test Series 12 and 13 because they did not use a standard LS gasket, but DG (0.190" thick). These DG were used in lieu of the LS gasket because the stock of LS gasket was depleted before testing finished. The DG arrangement was two gaskets made of the same material as a standard LS gasket, but the total thickness was 0.190 inch, which may lead to non-prototypic results. Finally, Test Series 9 is discussed because this test started with two gaskets installed, both a fresh SR gasket (0.105" thick) and a fresh new-style LS-n gasket (0.150" thick). Test Series 9 is not prototypic of how gaskets would be changed, but it demonstrated the situation when two fresh gaskets are utilized at the same time.

3.7.1 Test Series 11: Sealing the HC with an LS-o gasket (0.120 inch) after Retorquing an SR gasket (0.105 inch) 2 Times

- Test 11A started with a fresh SR gasket, which has a nominal thickness of 0.105 inch and the HC was sealed with an initial torque of 736 ft-lbf. The test ended after 24 hours but in looking at the first 6 hours the value of the applied torque had dropped to 64% of its original value, **Figure 24**.
- Test 11B continued with the SR gasket of Test 11A, which was retorqued to 665 ft-lbf. As previously shown, after a retorque of an SR gasket, the loss is less and slower. Of the initial applied force 90% was still retained after 6 hours. However, as seen in all tests the force continues to drop, even after 96 hours. When the Test 11B terminated, it dropped to 86% of the initial value, **Figure 25**.

- Test 11C, which was a 2nd retorque of the SR gasket started in 11A, after 2 hours 97% of the initial torque of 668 ft-lbf was still retained, as compared to the fresh SR gasket of Test 11A at 2 hours of 64% was retained and to Test 11B, the 1st retorque of SR gasket of 11A at 2 hours of 93% was retained.
- Now the key test was Test 11D, which was with the addition of a fresh old-style LS-o gasket, that is, it had a nominal thickness of 0.120 inch, and the HC was torqued to 705 ft-lbf. The torque history of this gasket arrangement fell between the histories of the 1st and 2nd retorquing of the SR gasket. Test 11D was terminated after 4 hours, **Figure 25**, but seen better in **Figure 24**, when the initial torque dropped to approximately 77% of its original value.

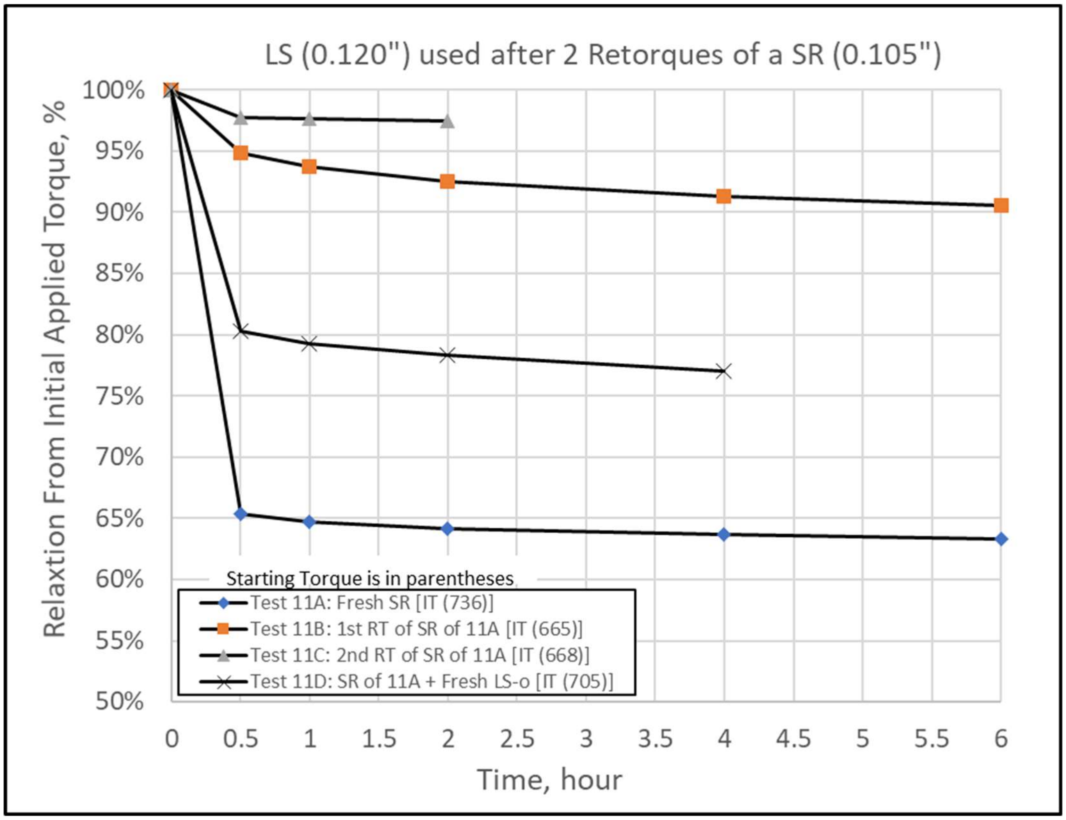

Figure 24: Early changes in applied torque to gaskets, SR & LS

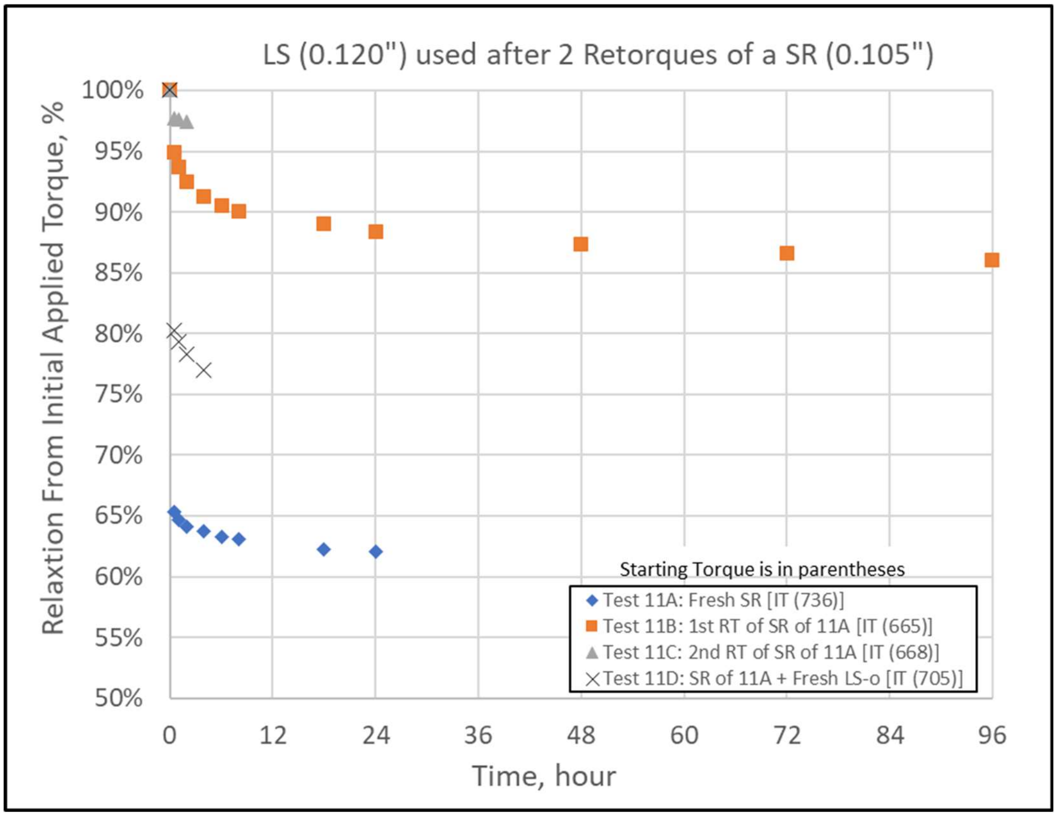

Figure 25: Changes in applied torque to gaskets, SR & LS

The series of Test 11 tests ended with two more tests to look at long-term responses, Test 11E, which was a simple retorque of the gasket arrangement of 11D, i.e., SR+LS-o, to 672 ft-lbf, continued for 2 days, and Test 11F (and additional retorquing in Test 11E), which continued for 18 days. During the first 4 hours of both tests, the retorquing of the double-gasket arrangement of Test 11D resulted in a drop of the initial torque to near 88%, shown in **Figure 26**, which is significantly less than the drop to 77% experienced from the initial torque (shown in **Figure 25**). Compare to Test 11D in **Figure 24**. For test 11F, **Figure 27**, after 18 days (432 hours) the initial torque dropped to approximately 79% of the its original value. From **Figure 28** it can be seen that by the end of Test 11F the value of the torque continued to drop but it was still above 500 ft-lbf, near 530 ft-lbf. Because Test 11E ended after 2 days it is not known if it would have been lower than 500 ft-lbf after 18 days. What is clear is that the applied force in a HC continues to drop several weeks after being sealed.

A rough linear extrapolation of Test 11F can be used to predict when the HC torque drops to 500 ft-lbf, below which leaks may occur. Using the more detailed results shown in **Figure 28**, then at 13 days (537.44 ft-lbf), 14days (537.42 ft-lbf), 15 days (535.12 ft-lbf), 16 days (534.63 ft-lbf), 17 days (533.30 ft-lbf), and at 18 days (533.06 ft-lbf) a linear fit to those data, with a relatively good correlation coefficient of R^2=0.93, predicts the torque will drop to 500 ft-lbs by day 51. This is not as good as for employing a fresh SR gasket, but once again, the test pressure of 150 psig is much higher than the typical operations pressures and the test pressure is being applied constantly, which is not expected to be prototypic, with fluid flows stopping and starting due to operational needs. The reason the gasket arrangement of a combined SR + LS gaskets may drop slightly faster than a simple SR gasket by itself is because the much thicker gasket material, i.e., SR(0.105")+LS-o gasket (0.120") probably permits more cold flowing as the thick gasket sandwich arrangements relaxes under the stress from the applied torque.

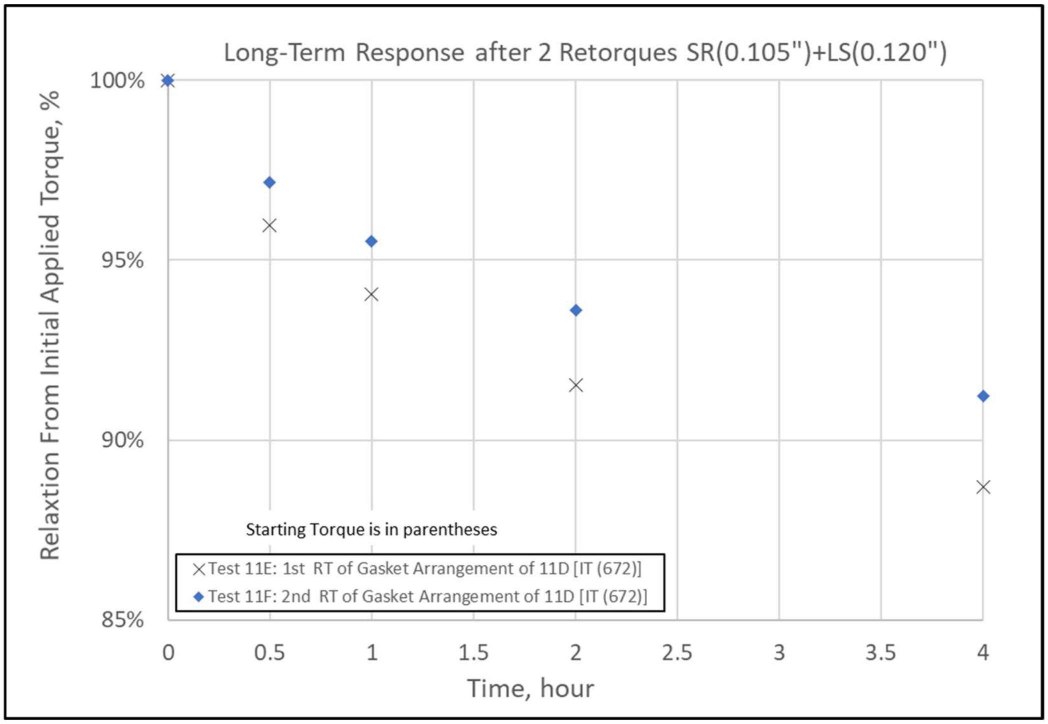

Figure 26: Early percentage changes in applied torque to gaskets, SR + LS

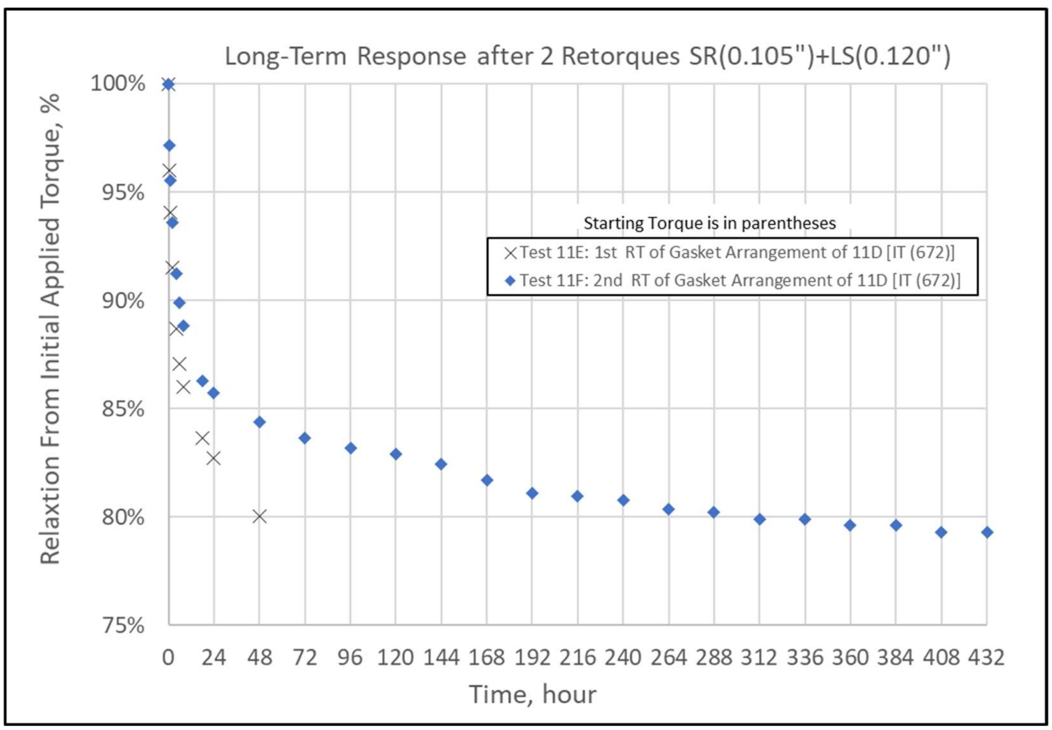

Figure 27: Percentage changes in applied torque to gaskets, SR + LS

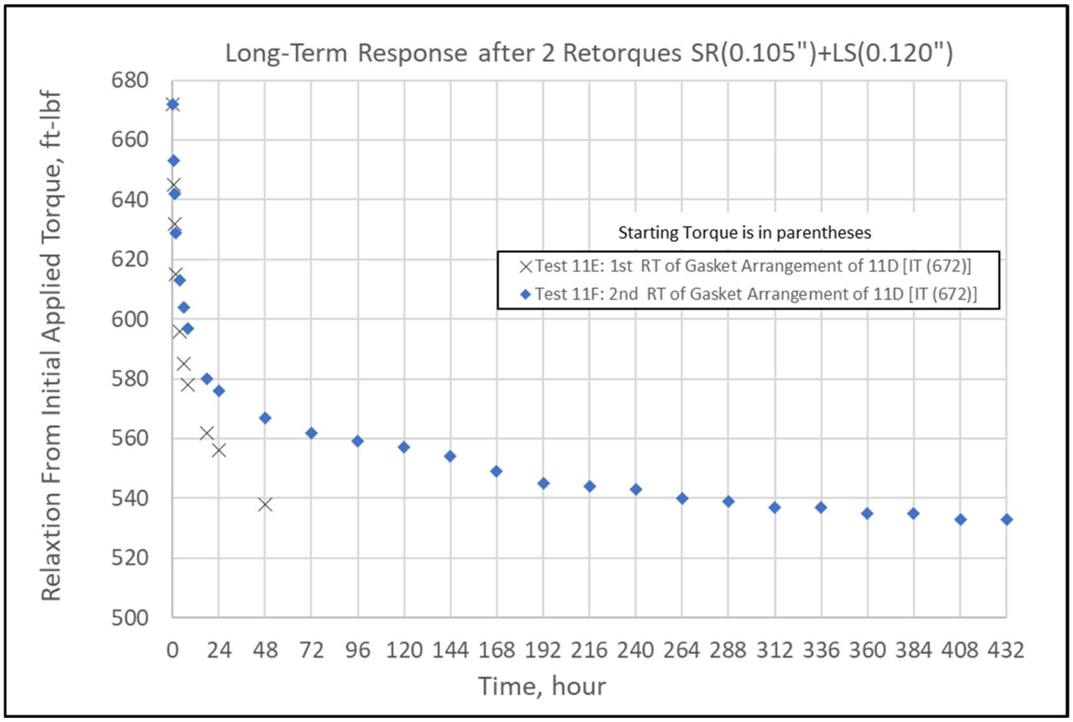

Figure 28: Changes in applied torque to gaskets, SR + LS

3.7.2 Test Series 10: Sealing the HC with an LS-n gasket (0.150 inch) after Retorquing an SR gasket (0.105 inch) 1 Time

Test Series 10 was similar to Test Series 11 with the exception that the SR gasket was only retorqued once and the LS gasket was the new style gasket, LS-n, which is thicker (0.150”). Even so, the trends are similar. In Test 10A the loss of applied torque of a fresh SR gasket exhibits a steep drop to approximately 75% of the initial torque after the first 30 minutes, dropping to 74% after 6 hours (see **Figure 29**). After one retorque of the fresh SR gasket, Test 10B, the loss in applied torque is significantly less. It retained 97% after 30 minutes and 94% after 6 hours of the 705 ft-lbf initial torque. Then, after adding a fresh LS-n gasket, the loss of applied torque was similar to, but not as severe, the fresh SR gasket. After 30 minutes Test 10C demonstrated that the SR+LS-n gasket arrangement retained about 81% of the initial torque and after 6 hours it still retained about 79%. The addition of the new thick LS-n gasket exhibits significant relaxation, but as will be discussed next, by retorquing the SR+LS-n gasket arrangement, the relaxation can be reduced.

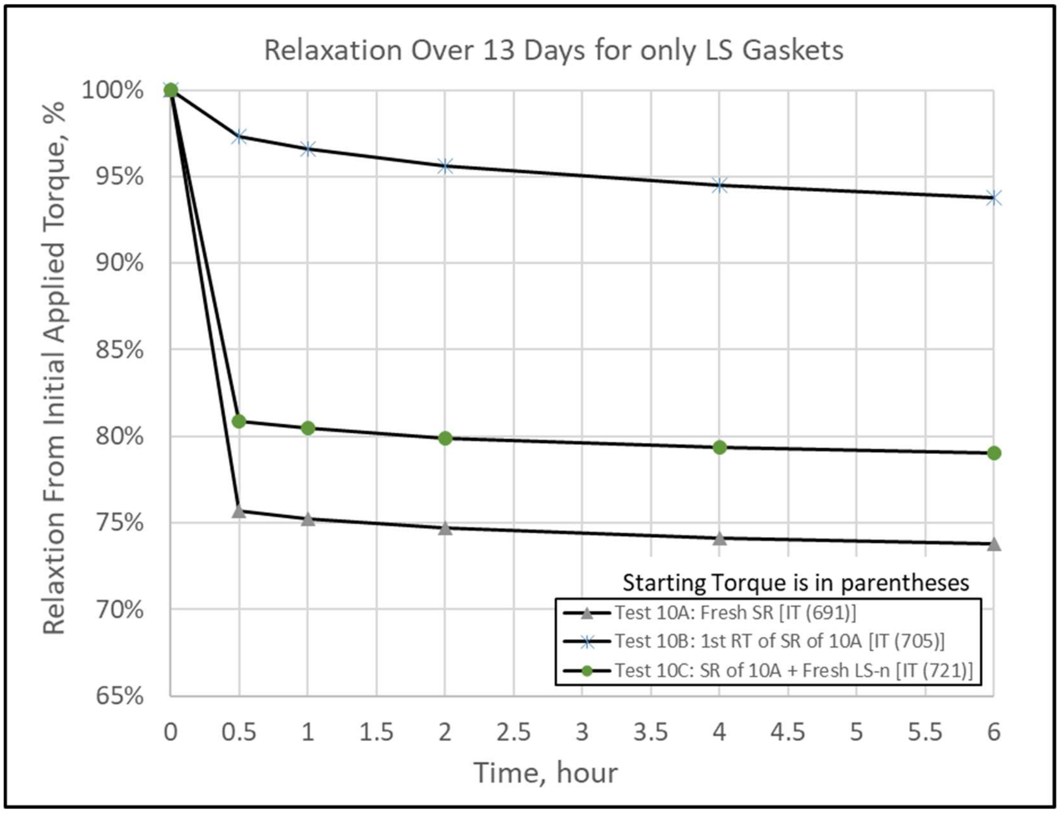

Figure 29: Early percentage changes in applied torque to gaskets: SR & LS

Figure 30, shows the results to the end of 10B, which was 72 hours. Once again, the gaskets are a flowing media and the force applied to the HC continues to slowly drop for a considerable time. **Figure 31** shows the results of Test 10D, which was the final and longest test in Test Series 10 at 21 days (504 hours). Test 10C ended after only 6 hours, **Figure 29** and **Figure 30**, so for Test 10C the gasket arrangement of retorqued SR gasket with a fresh LS-n gasket (0.150-inch thick) was retorqued in Test 10D to demonstrate the relaxation response. Even after 21 days the initial applied torque was still at 86%. However, this test exhibited the closest to a gasket relaxation coming to steady state. Shown in **Figure 32** are data from the last four days of Test 10D, days 18 to 21. The measured torque was changing very little but while the changes were small, they were still dropping. However, while an asymptote was not reached the slope of the reduction in torque with time is more than an order of magnitude less than for Test 5, **Figure 12**, A rough linear extrapolation of the trend line predicts that it would take almost 2 years for the applied torque to drop below 500 ft-lbf. It appears that retorquing the gasket combination of SR+LS-n shortly after the initial torque seemed to be very beneficial.

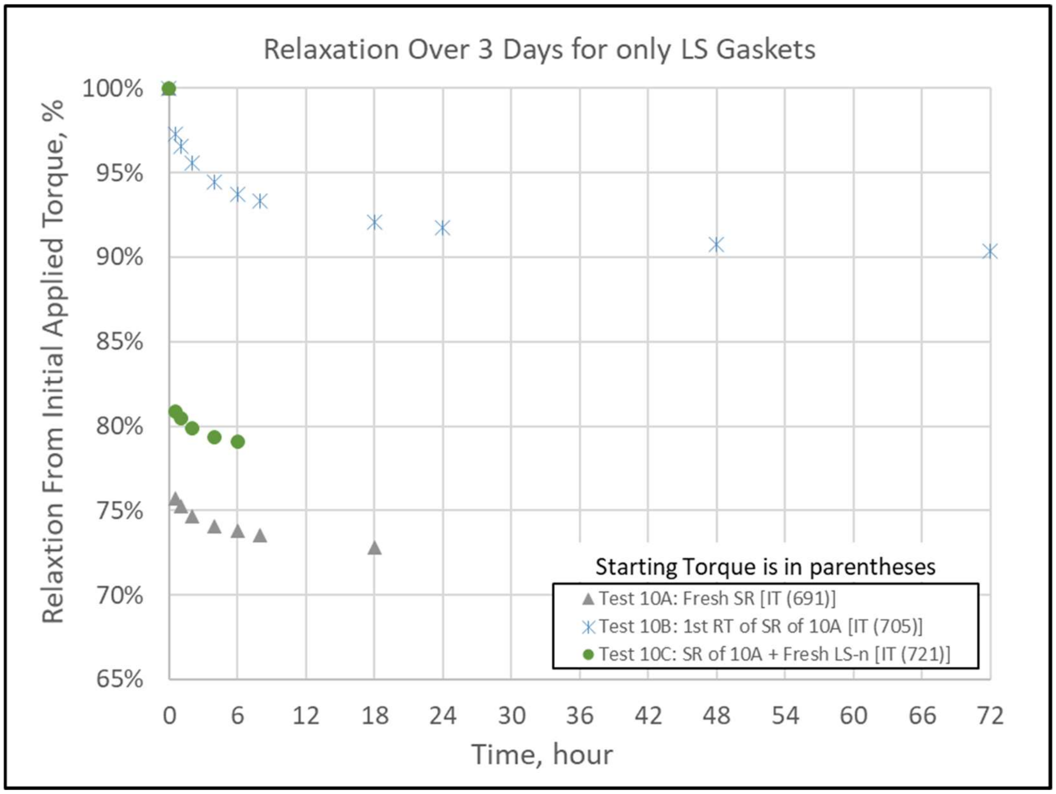

Figure 30: Percentage changes in applied torque to gaskets: SR & LS

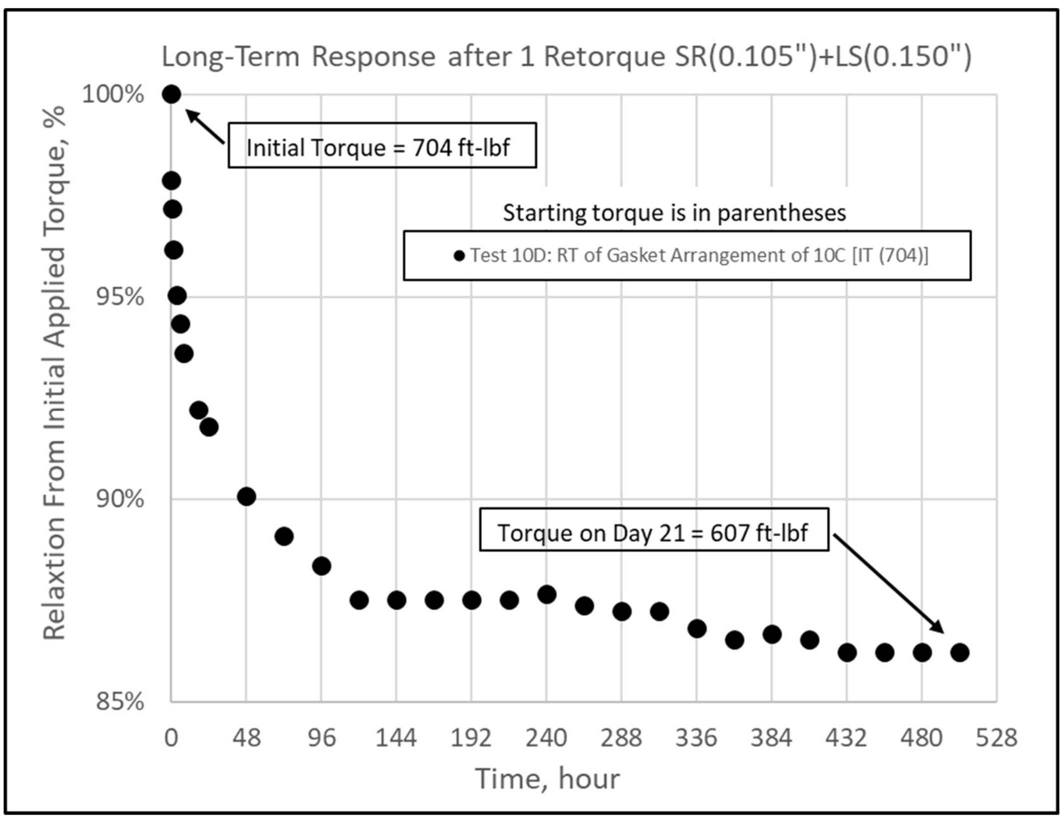

Figure 31: Percentage changes in applied torque to gaskets: SR & LS

Now as discussed earlier in Section 3.2: Gasket Relaxation, the reason for the periodic fluctuations of the torque by ±1 ft-lbf twice a day was most likely due the daily fluctuations of the outside temperature. **Figure 32** shows that high peaks occurred in the late evening, when it is warmer, thus increasing the system pressure (due to the expansion of fluids with temperature) leading to an increase of the force on the HC. Conversely, the low peaks occurred during the early morning, when it is cooler, thus reducing the system pressure leading to a reduction of the force on the HC, i.e., the force opposing the gasket sealing force. The small volume of water, around ½ gallon, was pressurized within the nozzle-HC cavity. Note, this is not prototypic to the large HCA piping system. The small water volume could expand or contract as it reacted to the morning to evening temperature swings, causing the applied HC load to fluctuate ±1 ft-lbf, or approximately the ± 0.2% shown in **Figure 32**. To emphasize that the fluctuating torque values are directly connected to temperature, which affects the internal pressure of the HC cavity, which in turn affects the HC applied force, see **Figure 33**. That figure shows that the initial applied pressure dropped from 150 psig to approximately 85 psig, after more than 2 weeks of operation. More importantly, the same fluctuations in the applied torque value are seen in the fluctuating pressure values between 87 and 81 psig over the same period shown in **Figure 32**. The peaks and valleys almost match. The pressure reaction preceded the torque reaction as it should.

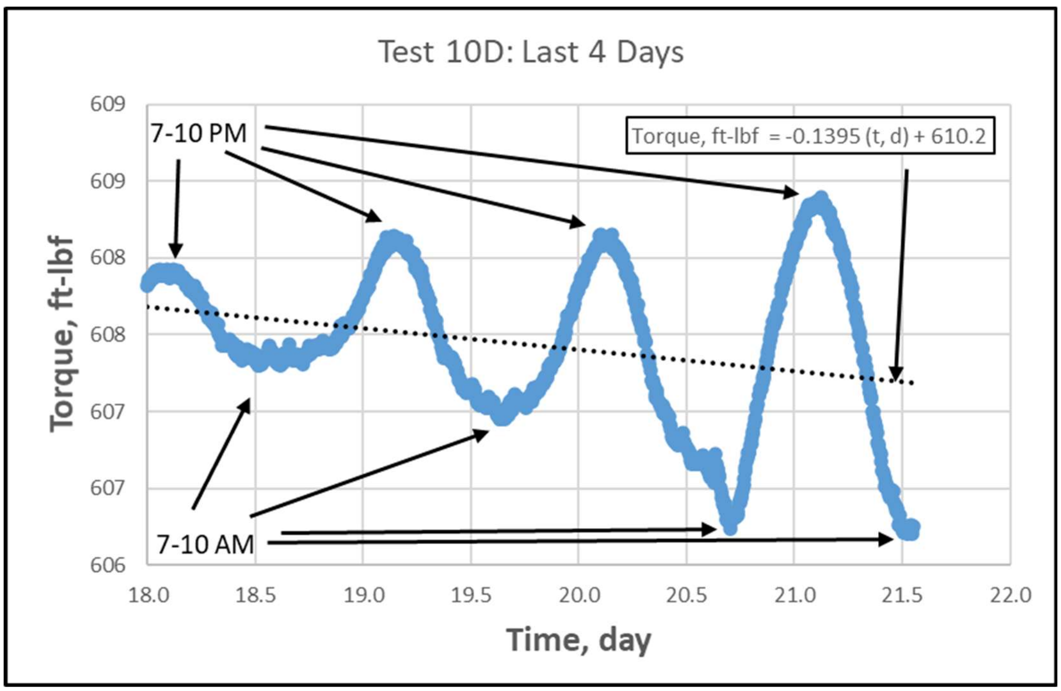

Figure 32: Last 4 days of dropping and fluctuating torque during Test 10D

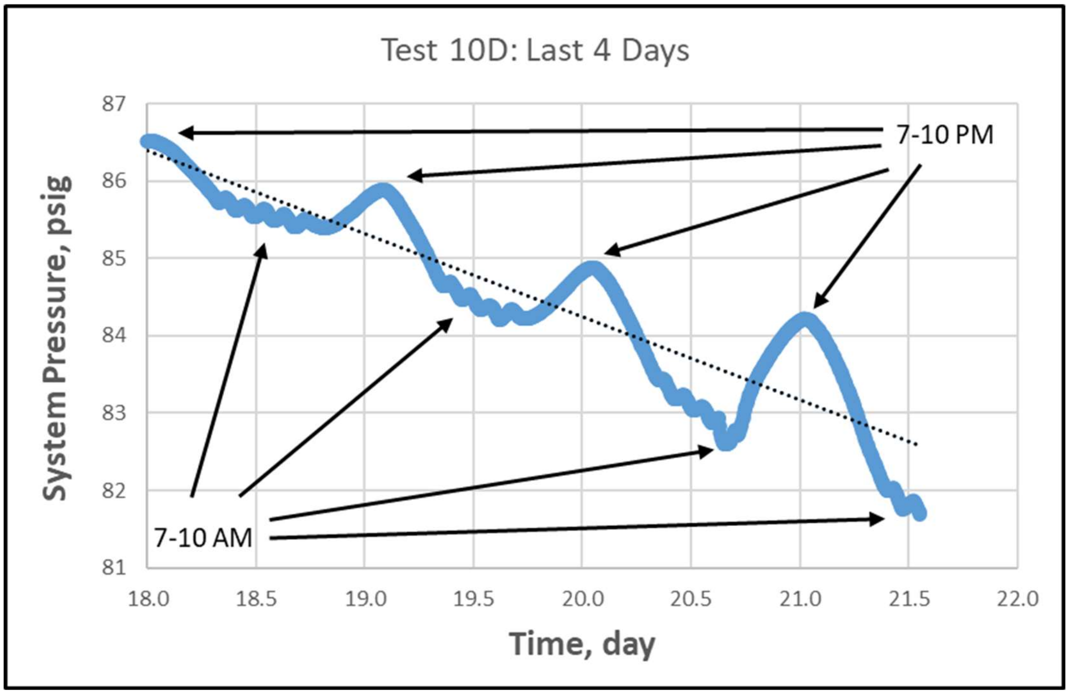

Figure 33: Last 4 days of dropping and fluctuating pressure during Test 10D

3.7.3 Test Series 12 Sealing the HC with a DG (0.190 inch) after Retorquing an SR gasket (0.105 inch) 3 Times

For Test Series 12 the fresh SR gasket in Test 12A reacted similarly as previously discussed, in that, with a fresh gasket, the loss of the initial applied torque was significant, dropping to 80% of the starting value in the first thirty minutes and then down to approximately 77% after 4 hours (when the test ended, **Figure 34**). For the first retorque of the SR gasket, Test 12B, the initial applied torque was retained better. At 4 hours approximately 84% of the initial torque was retain. For the second retorque, Test 12C, the torque was still at 96% of the original value at 4 hours. On the 3rd and final retorque, Test 12D, the loss of the initial torque fell between the 1st and 2nd, which can be seen in **Figure 35** of the full test period of 6 days (144 hours). What was not typical was the response of the much thicker DG. As shown for Test 12E, after only 30 minutes the initial applied torque drop to approximately 60% and at the end of this test, at 48 hours, it was down to 45%. The DG performed significantly worse than either of the different types of LS gaskets. From Test 12E it is seen that the DG retained 55% of its initial torque at 6 hours, from Test 10C, the 79% of the initial toque was retained after 6 hours, **Figure 29**, and from Test 11D a similar amount of the initial torque, 77%, was retained at 6 hours, **Figure 25**. Furthermore, at only 45% of the initial torque, the resulting torque value of the SR+DG gasket arrangement of Test 12E was approximately 350 ft-lbf (**Figure 36**) which is significantly below the 500 ft-lbf threshold when leaks have been observed [2]. The DG was much thicker (0.190 inch) versus the thickness of the LS gaskets at either 0.150 inch for the new style, LS-n, and 0.120 inch for the old style, LS-o. Furthermore, as the double-gasket name implies, it was two gaskets sandwiched together to simulate an actual LS gasket. While the material of the DG was the same as for the other LS gaskets, the DG was thicker because it was two gaskets joined together. The fact it was not a single gasket may be the reason for the worse performance as for the DG-type LS gasket. Because the applied torque dropped to significantly to near the 312 ft-lbf threshold for a potential leak, this gasket arrangement would not be recommended for sealing a leaking HC.

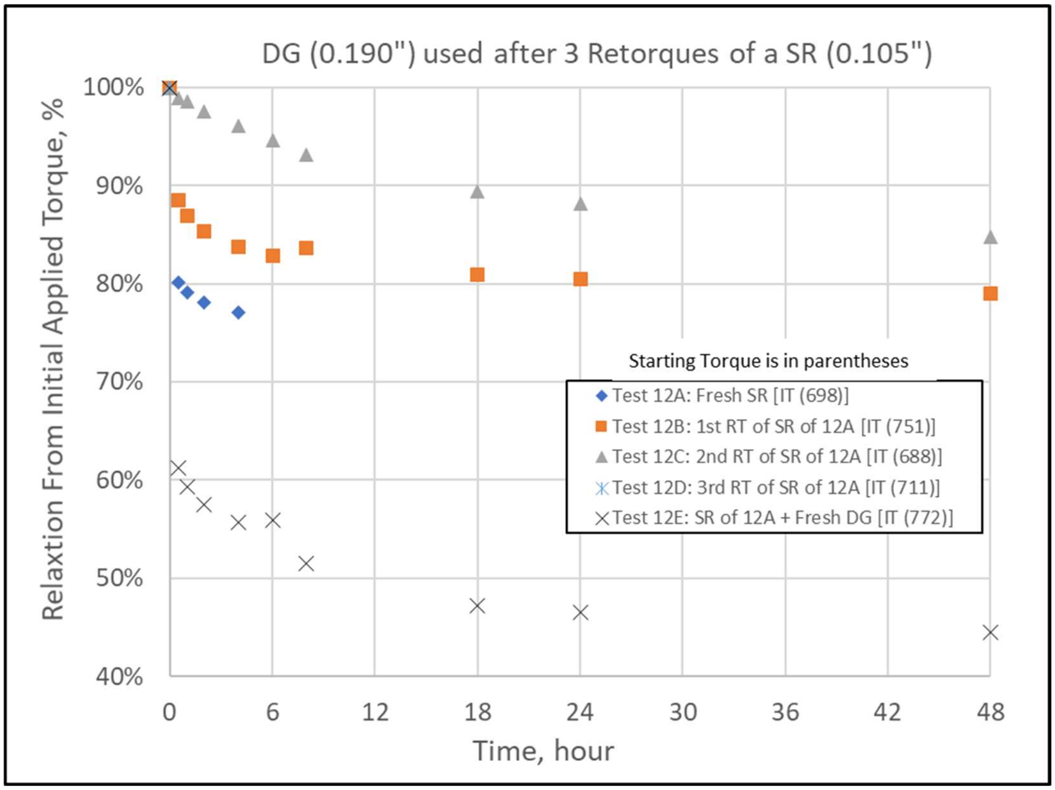

Figure 34: Percentage changes in applied torque to gaskets: SR & DG, 1st 2 days

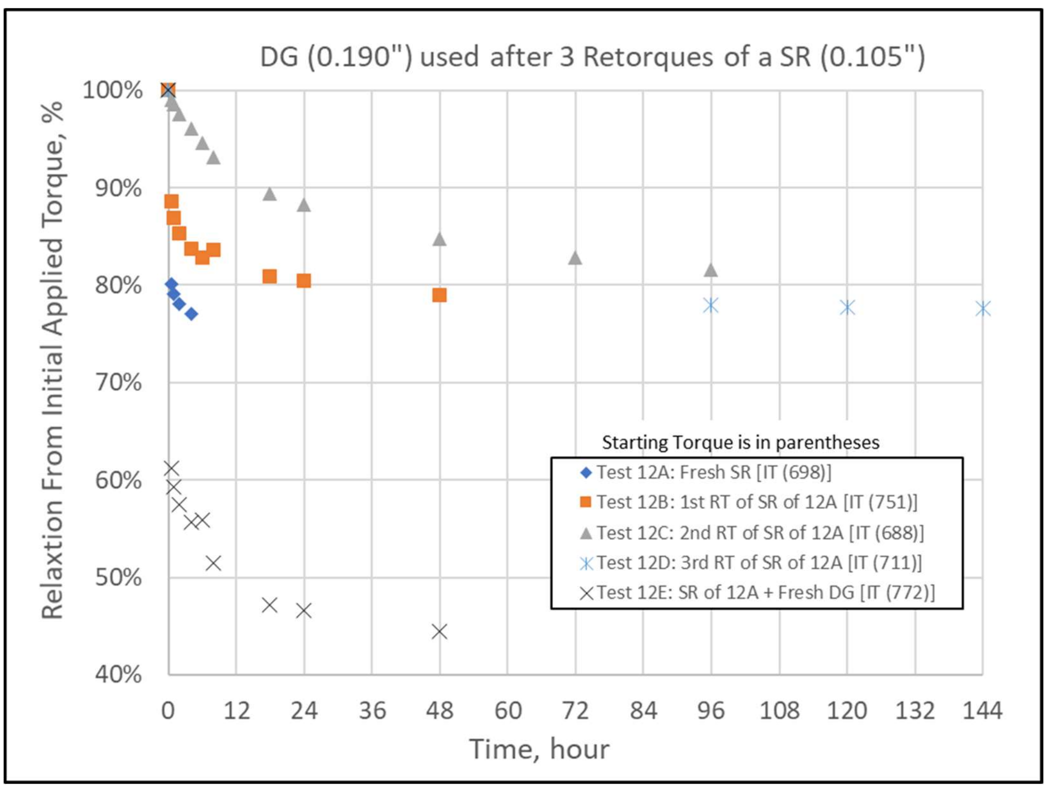

Figure 35: Percentage changes in applied torque to gaskets: SR & DG

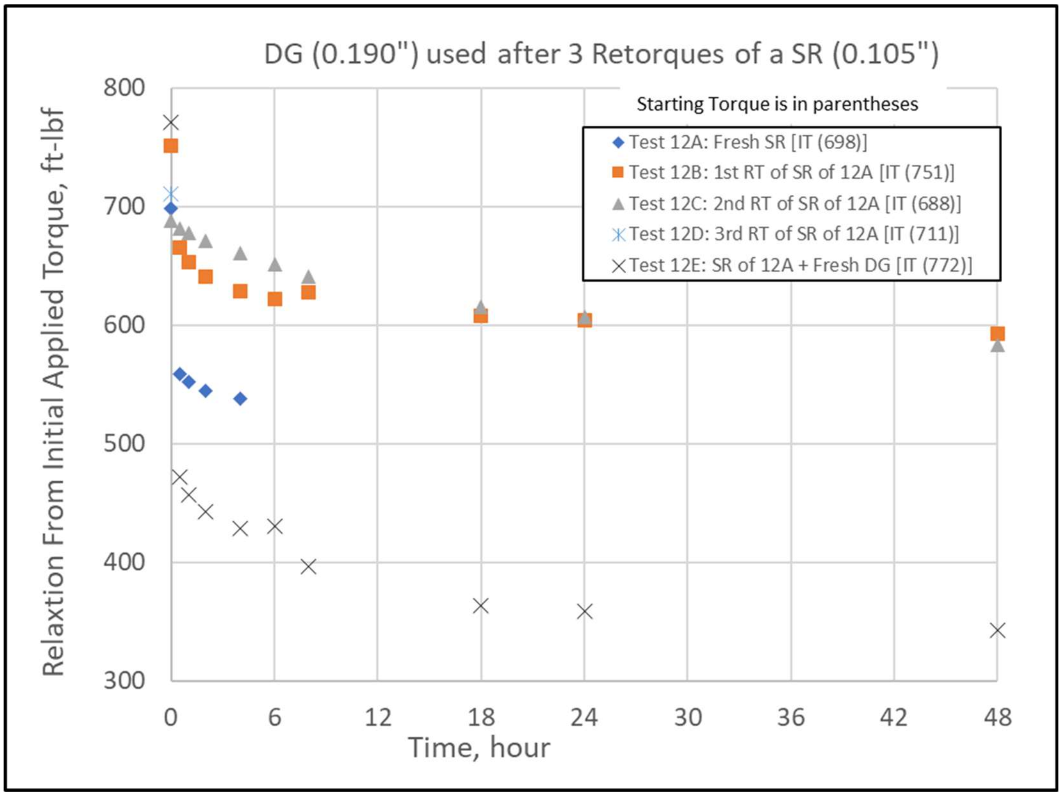

Figure 36: Torque changes in applied torque to gaskets: SR & DG

Test 12F resulted in a slight improvement for the SR+DG gasket arrangement when both gaskets from Test 12E were retorqued, **Figure 37**, but it still resulted in a poorer performance than any similar gasket arrangement of a SR+LS. For the old-style LS-o gasket, shown as Test 11F, **Figure 29**, the initial torque dropped to 79% after 18 days. For the new-style LS-n gasket, shown as Test 10D, **Figure 31**, the initial torque dropped to 76% after 18 days. For the results of the SR+DG gasket arrangement seen in **Figure 37**, the initial torque of 563 ft-lbf dropped to 310 ft-lbf after 432 hours (18 days), which is 55%, or at least 20% less than from the other SR+LS gasket arrangements. Furthermore, the percentage drop is most likely even larger because the initial torque is assumed larger than the measured 563 ft-lbf. At the start of Test 12E the HC was retorqued without increasing the data logging frequency to every second instead of its previous setting of every 5 minutes. This likely resulted in missing the initial torque value when it was set. As previously discussed, **Figure 15**, the first 5 minutes are crucial. The important fact is that the torque was only approximately 300 ft-lbf after 18 days. There is potential to leak at that point.

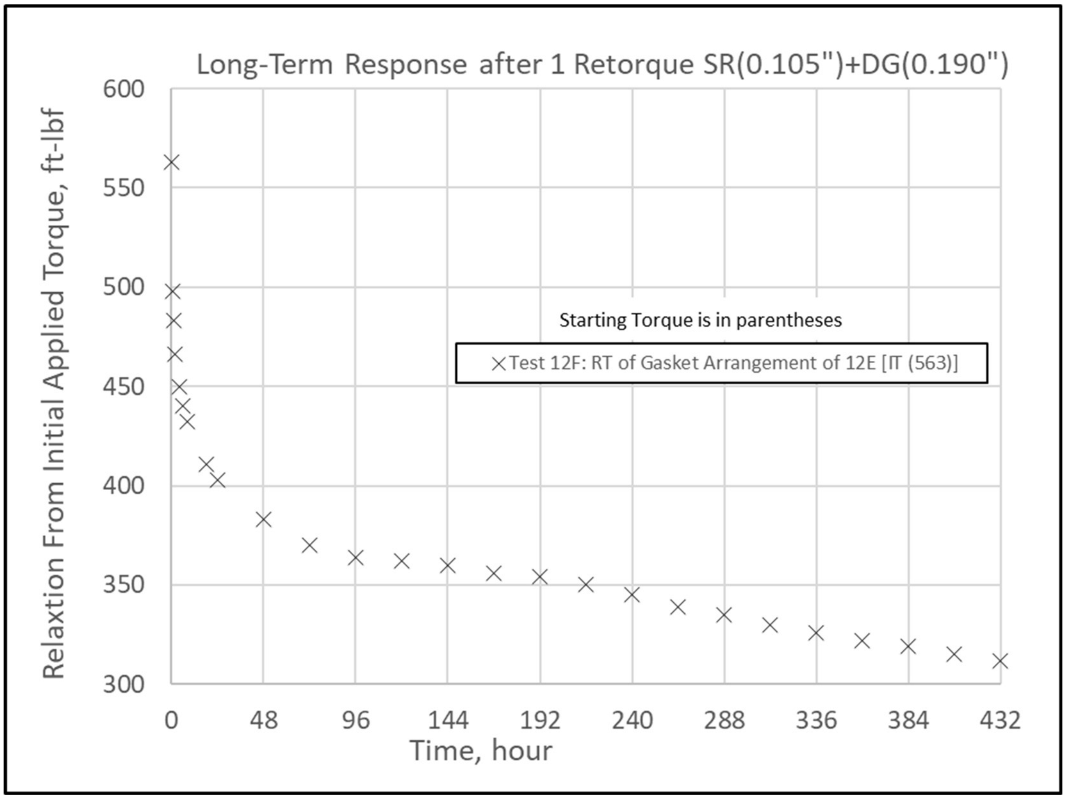

Figure 37: Torque changes to retorquing the SR & DG gasket arrangement

3.7.4 Test Series 13: Sealing the HC with a DG (0.190 inch) after Retorquing an SR gasket (0.105 inch) 1 Time

Test Series 12 was repeated in Test Series 13 as shown in **Figure 38**, **Figure 39**, and **Figure 40**. However, for this test series the SR+ DG gasket arrangement performed significantly better for some unknown reason. As in previous tests, the initial applied torque to a fresh SR gasket, Test 13A, drops quickly and after 6 hours it is down to approximately 90%. The retorqued SR gasket performed better, Test 13B, because it retained just above 98% from the initial torque at 6 hours. After including the DG and retorquing the gasket arrangement to 725 ft-lbf, Test 13C, it dropped to 86% of that value in 4 hours, which was when the test was terminated. Compared to Test 12E in Test Series 12, which dropped to 55% of the initial torque, in the first 4 hours, **Figure 34**, the performance was superior. In fact, it seemed to perform even better that the SR+LS gasket arrangements. For Test 10C the initial torque dropped to 79% after 4 hours, **Figure 29** and for Test 11D it dropped to 77% of the initial torque after 4 hours, **Figure 24**. When the SR+ DG gasket arrangement was retorqued, the performance improved as it did for other SR+LS gasket arrangements. As seen in **Figure 40** even after 22 days (528 hours) the initial torque of 690 ft-lbf for the second retorque was still at approximately 655 ft-lbf, or 95% of the starting torque. Based on the poor performance of the SR+DG gasket arrangement in Test Series 12 and its superior performance in Test Series 13, a conclusion cannot be made about its performance. It appears that it would be too risky to assume that it would perform as well as the standard SR+LS gasket arrangements, be it the 0.120-inch LS-o or the 0.150-inch LS-n. The DG presents unknowns that would be hard to quantify without further extensive testing.

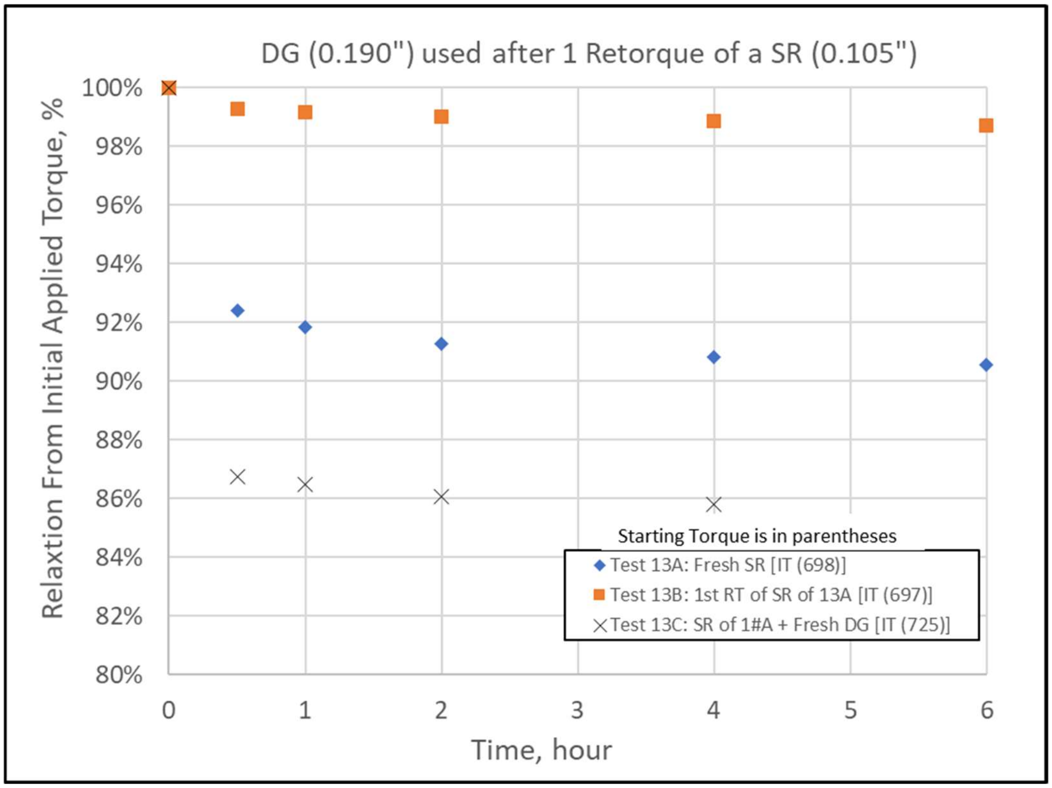

Figure 38: Percentage changes in applied torque to gaskets: SR & DG, 1st 6 hours

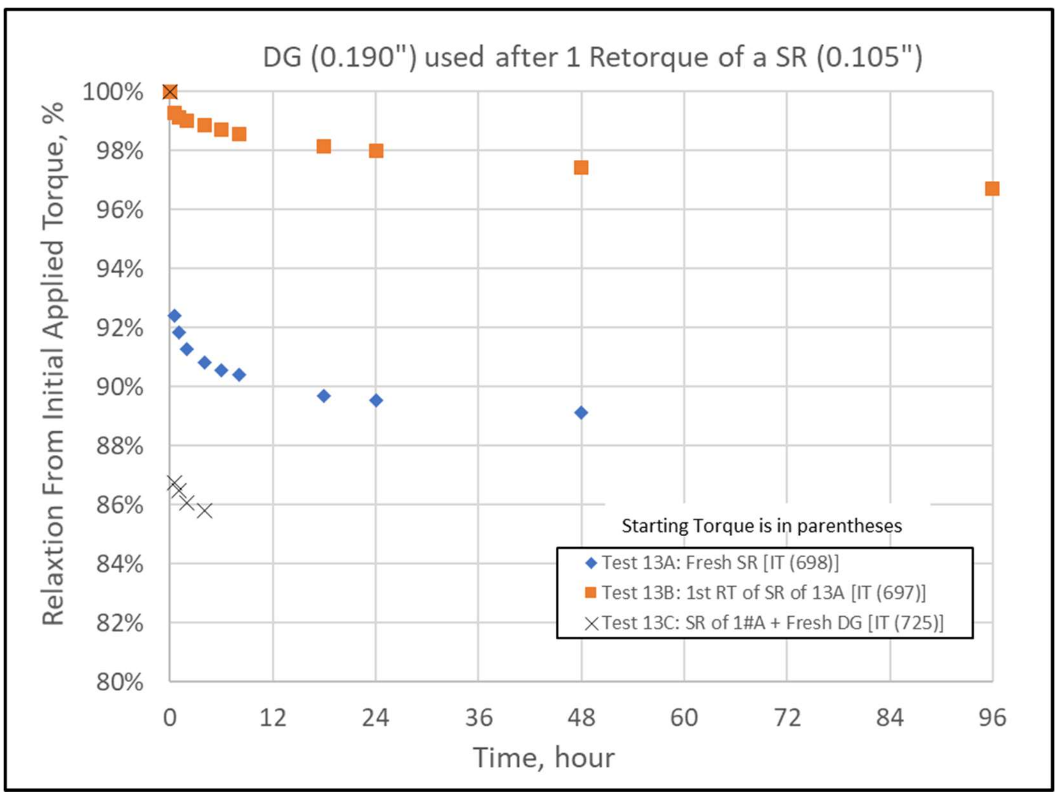

Figure 39: Percentage changes in applied torque to gaskets: SR & DG, 1st 4 days

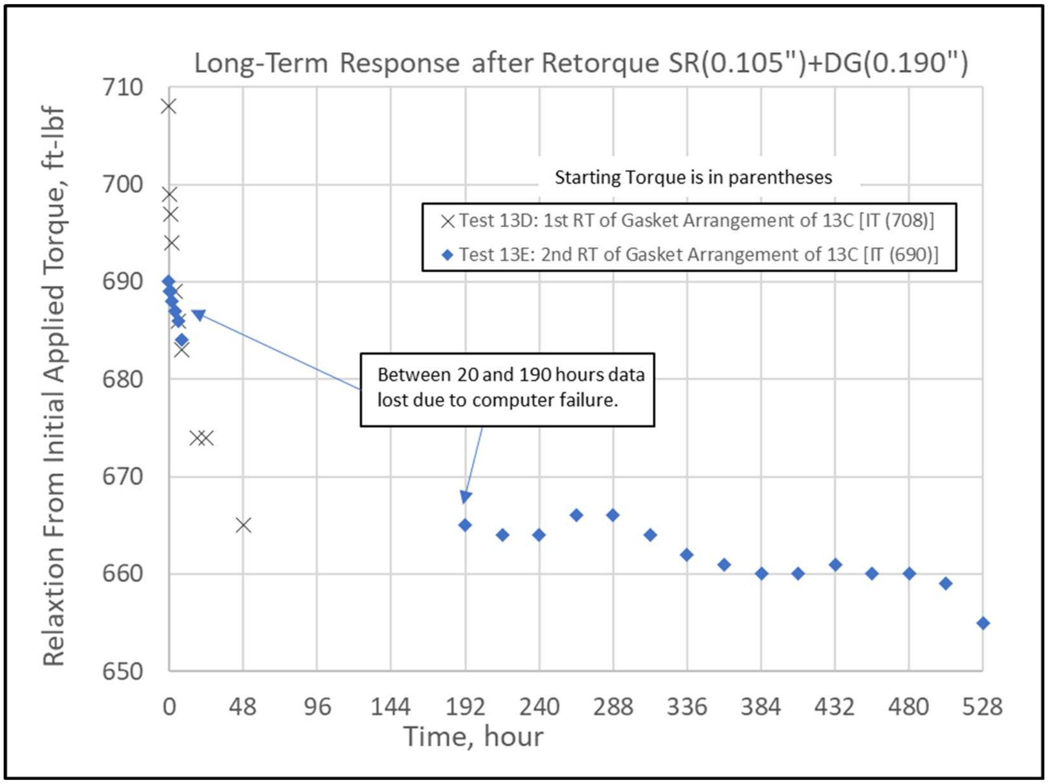

Figure 40: Torque changes to retorquing the SR & DG gasket arrangement

3.7.5 Test Series 9: Sealing the HC with a fresh LS-n gasket (0.150 inch) and a fresh SR gasket (0.105 inch)

Test Series 9 was unique because the first test, Test 9A, started with a fresh SR gasket and fresh LS-n gasket without first retorquing of the SR gasket, **Figure 41**. Then Test 9B followed with a single retorque of both gaskets together. Finally, for Test 9C the LS-n gasket was changed for a fresh LS-n gasket, without removing the original SR gasket. **Figure 42** depicts the first 6 hours of those tests where most of the reduction of the initial applied torques occurred. Since the type of gasket replacement is not what is expected in the field, the use of the data is limited. However, there are some aspects of this test series that are like the previous tests. That is, the fresh gaskets always demonstrate the largest drop from the initial applied torque. In **Figure 42** the two fresh gasket arrangement, Test 9A, retains 85% of the initial torque after 6 hours. After that gasket arrangement is retorqued the torque was still at 99% of the initial torque, after 6 hours. These results were expected based on what has previously been discussed. However, what is unique, and important, with this test series, is that it was the only test series in which an LS-type gasket was removed after being sealed with a SR gasket. For Test 9C, the LS-n gasket, which was used with the original SR gasket in Tests 9A and 9B, was replaced with a fresh LS-n gasket, leaving the original SR gasket. Test 9C showed that the drop in torque of the arrangement of a used SR gasket and fresh LS-n gasket was dramatic. It only retained 71% of its initial torque after 7 days (168 hours), seen in **Figure 41**. Most of this drop, i.e., to 75% of the initial torque, occurred during the first 6 hours, which is seen better in **Figure 42**. Why was such a large drop in torque experienced when the gasket arrangement was retorqued? The key may be in the process of the LS gasket replacement.

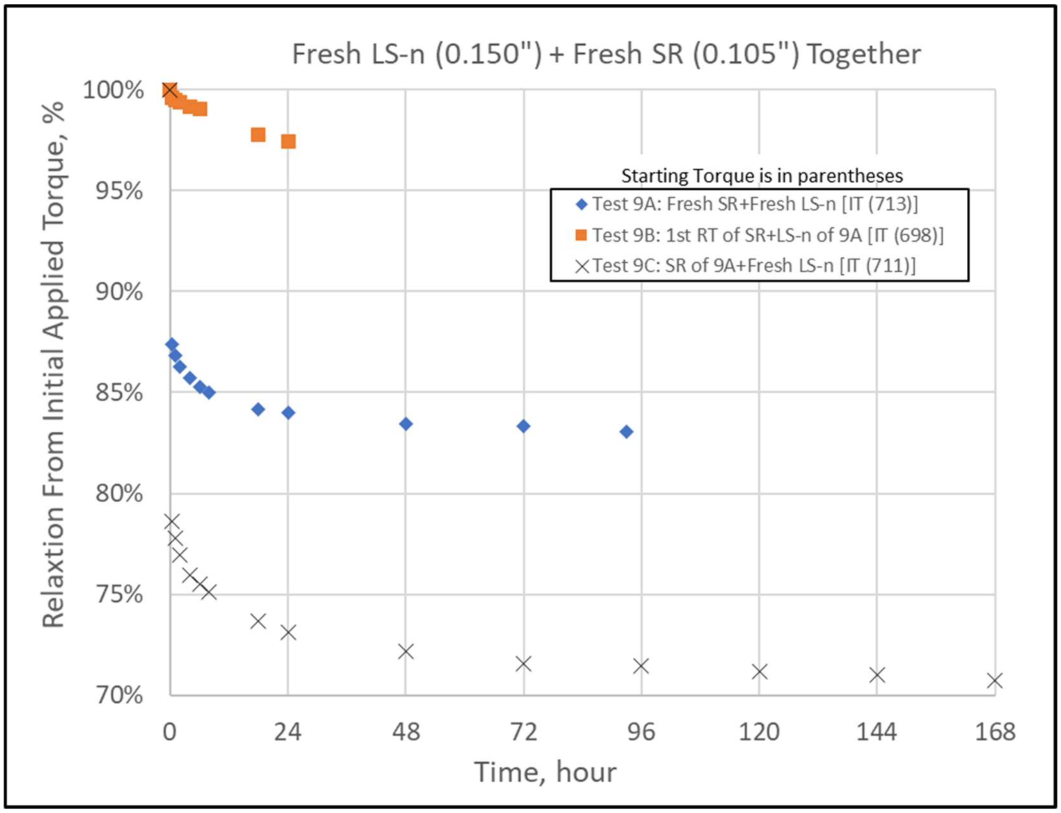

Figure 41: Percentage changes to SR & LS-n gasket arrangement

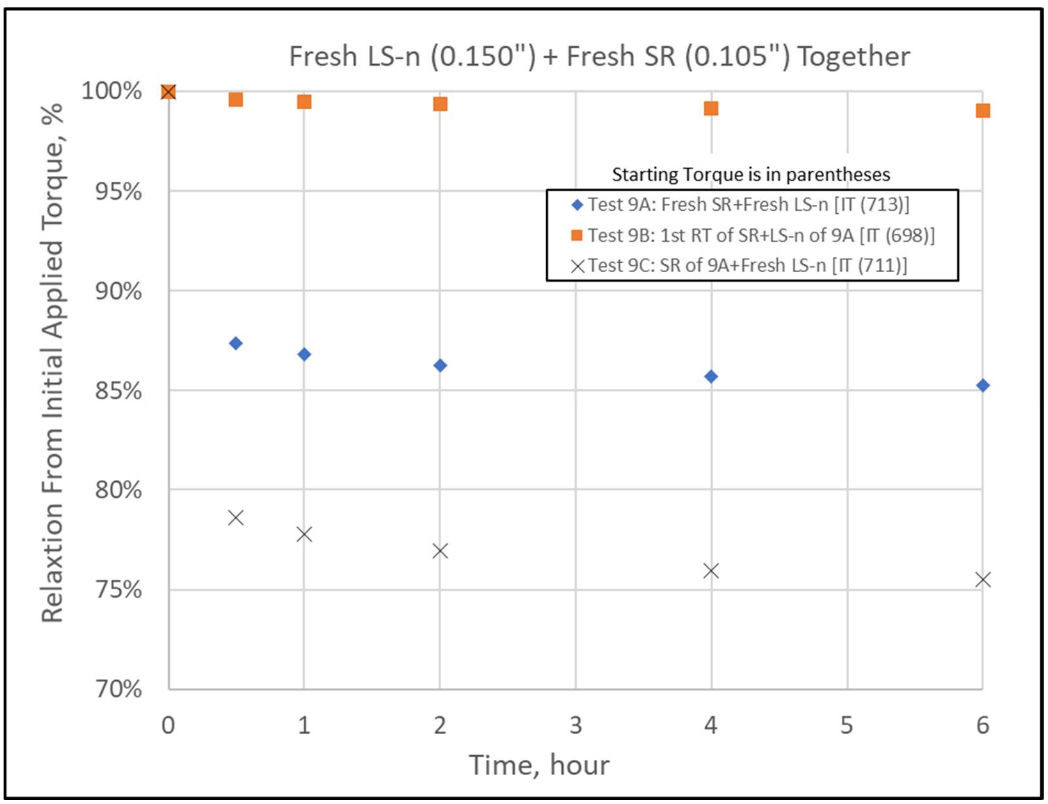

Figure 42: Early percentage changes to SR & LS-n gasket arrangement

After the used LS gasket was separated from the original SR gasket there was noticeable damage, **Figure 43**. What the photograph shows is that before beginning Test 9C with a fresh LS-n gasket the old LS-n gasket was removed by separating it from the installed SR gasket. The original SR gasket, which is the larger ring of gasket material in the photograph, is basically intact. However, the removed LS-n gasket still had bits and pieces of the gasket fibers stuck to the bottom of the HC block and on the SR gasket. Basically, the LS-n gasket came off in pieces. When the fresh LS-n gasket was installed in the HC, it came in contact with the used SR gasket and the vestiges of the old LS-n gasket. Most likely, when the two new gaskets were initially forced together during the torquing process, to start Test 9A, the fibers of the fresh material intertwined as they were compressed. Once sealed it appears that the two gaskets are joined to the point that permanent damage occurs if an attempt is made to separate them. Therefore, this implies that an employed LS gasket should never be replaced by itself. If an SR+ LS gasket arrangement successfully seals the connection, then when the sealed connection experiences another leak both the LS gasket and the SR gasket should be removed and a new SR gasket be used, to start the sealing process again.

Figure 43: Remnants of the removed LS gasket on the HC block after being sealed together with an SR gasket

3.8 Estimate Loss of Torque from Tests with Longest Test Periods

A discussion was already made on how the drop in torque occurs well beyond the available data and it is important to estimate when gaskets will relax to the point that the applied torque drops to 312 ft-lbf, which is the required torque limit for post seismic leak tightness [8]. Predicting the reduction of torque beyond the test data was roughly done by a linear extrapolation of the last several points from some select tests to illustrate that loss in time of the initial applied torque is continuous, e.g., see Section 3.2, "Gasket Relaxation." To hopefully obtain a slightly more accurate idea of the torque trends with time, data over the entire time periods of four tests were investigated, which ranged from 13 to 21 days. **Figure 44** depicts those data that were best fit to logarithmic trends, which the data seem to follow well. Those four tests are:

1. Test 5 used a fresh SR gasket (0.105-inch thick) with an initial torque to 696 ft-lbf.
2. Test 7 used a fresh LS-n gasket (0.150-inch thick) with an initial torque to 681 ft-lbf.
3. Test 10D, used both SR and LS-n gaskets that were retorqued to 704 ft-lbf.
4. Test 11F, used both SR and LS-o (0.120-inch thick) gaskets that were retorqued to 672 ft-lbf.

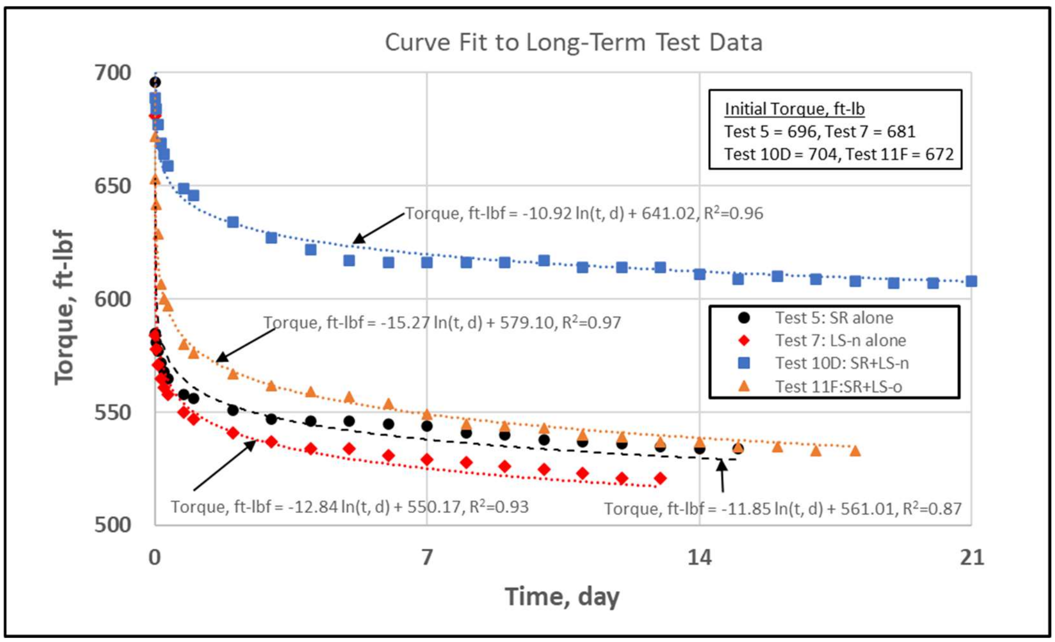

Figure 44. Least-square logarithmic to data for Tests 5, 7, 10D, and 11F

Also discussed in Section 3.2, is the fact that the drop of the applied torque to the HC initially occurs fast, especially in the first few days and then slowly tapers off, but loss of torque never seems to stop. The data do follow well a logarithmic trend and fitting a least-square curve to the data appears to represent nature of the drop in torque with time, especially during the first few days. However, the nature of a logarithmic trend is that it never reaches an asymptote. To find when the slope of a curve goes to zero its first derivative is taken and set to zero. For a curve like Torque(t) = A(ln(time)) + B, with A and B being constants, the first derivative is dTorque(t)/dt = A/time. The only way to satisfy dT(t)/dt = 0 is for the time to go to infinity. Even checking the time necessary for the logarithmic curves to reach 312 ft-lbf it would be more than thousands of years. While gasket relaxation may not be a fast process it will not relax forever. Furthermore, knowing that HC gaskets throughout HCA periodically leak [2, 5], a more realistic time frame is needed. While failure frequency is not known for each gasket in HCA, the timeline to a leak is finite. More prototypic testing is recommended.

Using a logarithmic model works well for the first few days, but after approximately 1 week the data appear to trend linearly, which is a more conservative trend. To see this fact, a linear least-square fit was made of the data from the last 10 days for each of the tests shown in **Figure 44**. Those data and curve fits are shown in **Figure 45**. The fits have correlation coefficients of better than 0.8 and in fact, for three of the tests the coefficients were above 0.95, which indicate the data followed a linear trend well after the first few days.

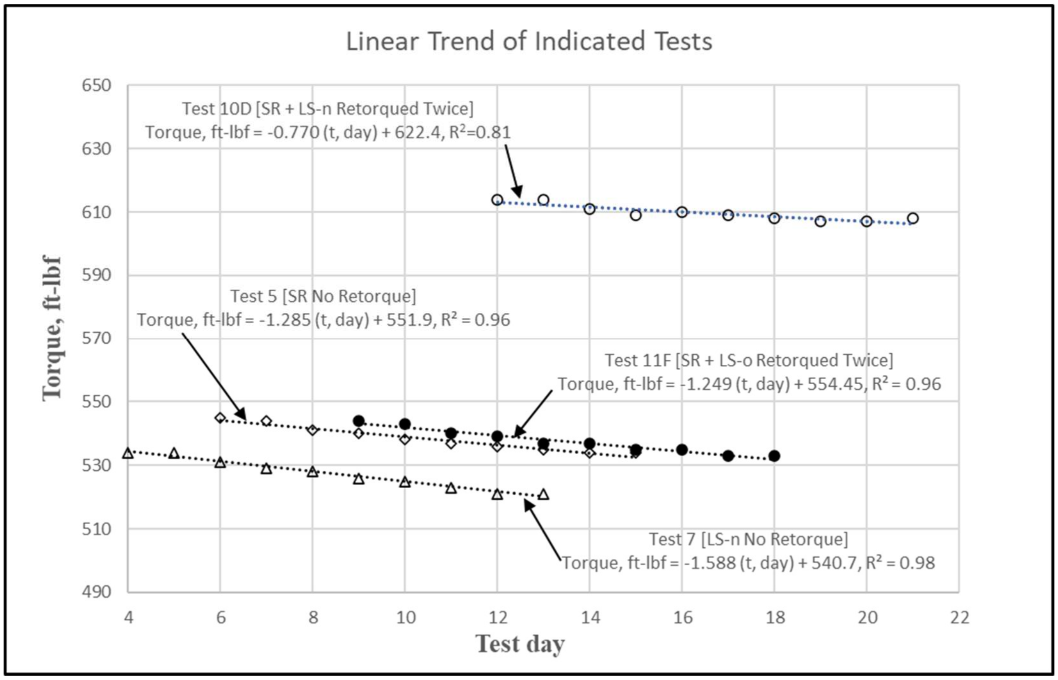

Figure 45. Least Square Linear Curve fit to last 10 data points of Tests 5, 7, 10D, and 11F

Table 4 shows the time estimate for the applied torque to drop to 312 ft-lbf by using the linear models depicted in **Figure 45**. Also included in the table are the standard errors calculated for the slope and intercept for each of the data sets. In determining the uncertainty of the time estimates the standard errors were multiplied by a factor of 1.96 so that they represent a 95% confidence interval. As expected, the gaskets that were not retorqued had the shortest times to reach 312 ft-lbf. However, Test 5, with a single SR gasket seems perform almost as good as the retorqued gaskets, i.e., Tests 10D and Test 11F.

Table 4. Estimated Time Necessary for HC Initial Torque to Drop to 312 ft-lbf.

Test	Gasket + Type Torque	Initial Torque	Duration	Slope (1)	Std Error (2)	Intercept (1)	Std Error (2)	Prediction to 312 ft-lbf (3)
No.	Arrangement	ft-lbf	days	ft-lbf/day	ft-lbf/day	ft-lbf	ft-lbf	months
5	SR with No Retorque	696	15 days	-1.28	0.10	551.89	1.06	6
7	LS-n with No Retorque	681	13 days	-1.59	0.07	540.70	0.66	5
10D	SR+LS-n Retorqued Twice	704	21 days	-0.77	0.13	622.40	2.18	13
11F	SR+LS-o Retorqued Twice	682	18 days	-1.25	0.09	554.45	1.29	6

(1) Slope and Intercept based on a least-square fit of last 10 days of test
(2) Statistical standard error of one standard deviation
(3) Prediction on the time necessary for the gaskets to relax to **312 ft-lbf**, based on linear extrapolation of test data

The gasket arrangement that lasted the longest, i.e., the gaskets for which the torque dropped the slowest was with the SR gasket and the newer LS-n gasket. Test 10D was performed with the use of both gaskets after they were retorqued twice. For that test, the estimated time for the initial torque value to drop to 312 ft-lbf was just over 1 year, i.e., 13 months.

This above presentation gives a fair estimate of the loss of toque with time. It is important to , but it is very important to remember that to predict the future from a limited data set always involves risk because the uncertainties have several sources to include:

1. The accuracy of the force measured from the stain gauges, which was calibrated to ±2% of reading. Furthermore, the overall force was the sum of the forces measured from each of the three Hanford Connector jaws, which leads to an average uncertainty of approximately ±3.5%, using the sum of the squares.
2. The accuracy of the torque obtained by the torque wrench, which had a calibrated uncertainty of ±2% of reading. Therefore, the combined uncertainty of the torque and the resulting applied forces, should be at least ±4%.
3. Reading the dial on the torque wrench, which was done by different people, may also introduce an unknown amount of uncertainty.
4. The accuracy of the conversion from force to torque was done once for each test series. For example, a test series began by setting up a gasket arrangement and then torquing the arrangement to some initial torque, e.g., 700 ft-lbf. At the point the torque-force conversion is set, so it is at its most accurate. The uncertainty is then what was discussed in the first two items. However, as the test proceeds and the force drops due to gasket relaxation, the accuracy of conversion may decrease, but this is unknown.

4.0 Conclusions

1. The torque response of using either a SR gasket (0.105-inch thick) or a LS-n gasket (0.150-inch thick) was the same, so should be sufficient to seal a HC by themselves. That is, the thicker LS-n gasket is acceptable for use.
2. Approximately 15% of the force from the torquing of a fresh SR gasket is lost in the first 5 minutes, but the loss may be as high as 33%.
3. Within the first 24 hours the sealing force from an initial torque to a fresh SR gasket drops by up to 38%.
4. Within the first 24 hours the sealing force from a re-torque to a fresh SR gasket drops by up to 20%. That is, retorquing a fresh gasket improves and slows down the loss of sealing force.

5. Thicker double-layered gaskets, DG = 0.190 inch, had conflicting results from good to poor performances; therefore, their use is not recommended.
6. Adding a fresh LS gasket, without removing an existing SR gasket, which has been previously torqued, leads to a sealed connection that still retains approximately 80% of its initial applied torque after 6 days. Adding a LS gasket to the previously used SR gasket is a good as changing a leaking SR gasket for a new SR gasket.
7. Retorquing the SR+LS gasket arrangement reduces the loss of applied torque to better than 85%, even after several weeks. Results show that the loss of applied torque never ceases, but retorquing can slow the loss to maintain the applied torque to better than 70% of its initial value for more than a year.

5.0 Recommendations

1. The applied system pressure during testing was not prototypic, starting high and slowly decaying with time. Actual system pressures must fluctuate as flows start and stop through pipes. In future tests it would be prudent to determine actual system pressures to be more prototypic. For example, the flow system pressure through HC should be low when nothing is flowing, which may be most of the time. In general, before further, similar testing, it would be beneficial to determine the prototypic environment. Unless the pressure is made more prototypic it may be better to not apply a pressure at all to eliminate the unknowns when evaluating changes in sealing forces on gaskets.
2. Gaskets relax with time causing the applied torque to drop. While most of the loss of applied load occurs in minutes and hours of the initial load, the loss slows but never stopped during the durations tested of up to 22 days. Longer-term tests, e.g., 6 to 8 weeks, should be performed to better predict the long-term loss with time.
3. Always install a new SR gasket after a joint containing a SR+LS gasket arrangement begins to leak. Trying to separate a LS gasket from a SR gasket causes damage to both seals.
4. Developing timetables to record when a HC is sealed and when it leaks would be useful to proactively retorque seals before a leak occurs to reduce the frequency of leaks throughout HCA. (A similar recommendation can be found in Reference [4].)
5. Without results from the preceding recommendation, a reasonable timetable to periodically retorque seals to minimize leaks could be developed from Table 4.
6. Procedure modifications required for reducing HC leaks:
    1. After the initial torque of a HC with a new SR or LS gasket, retorque the HC no sooner than 8 hours from the time of the initial torque.
    2. If a LS is used without removing the SR, two retorques of the HC should be performed. The first retorque to be performed no sooner than 8 hours from the initial torque and the second retorque no sooner than 8 hours from the first retorque.

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19. "Practical Strain Gage Measurements, Chapter E – Stain Gauge in Omega Catalog, 1999.

Appendix A. Test Data

The following **Table 6**, **Table 7**, **Table 8**, **Table 9**, **Table 10**, **and Table 11** include the HC data[3] for all the tests in the form of applied torque, rounded to an integer. Torque was obtained by converting the measured force obtained from the calibrated strain gauges on the HC jaws. Those tables are followed by 6 more tables that show the measured force, **Table 12**, **Table 13**, **Table 14**, **Table 15**, **Table 16** and **Table 17**. Note, that the listed recorded forces are slightly different from the actual applied forces. The placement of the stain gauges on each of the HC jaws was aligned with the jaw, see the calibration setup in Appendix B but once a jaw is in place, see **Figure 2**, the line of force to seal the connector is a small angle from the angle of a jaw. Therefore, the listed forces are slightly higher than the actual applied force by a few percent. However, with respect of applied torque this difference has no impact in that the changes to the calibrated torque from its initial value because they are based on percentage change of the forces as they change. The percentage change would be the same whether or not a small correction was applied to the forces because the correction is constant over the entire range of values.

Once a gasket arrangement was installed in the mock nozzle-HC test setup and the connector was closed an initial torque was applied with a calibrated torque wrench to the HC ACME screw. Each of the HC jaws was instrumented with a strain gauge to measure the applied force. For example, a torque of 700 ft-lbf applied to the HC generally resulted in a force of about 18,000 lbf on each of the three HC jaws, for a total of 54,000 lbf. When a test began, and the initial torque was applied a conversion factor was determined to relate the calibrated torque to resulting forces. The data in the table are listed in terms of the initial and changed HC forces, that is, the sum of the forces in the three HC jaws, in terms of torque based on that conversion factor. In most cases the initial applied torque drops with time as the installed gaskets relax because the material cold flows due to the pressure exerted. There are some exceptions, as noted in the tables, where the values of decreasing torque may increase temporarily which was thought due temperature affects to the strain gauge when ambient temperature fluctuated. However, in general these instances of increase torque values are very few.

For all Test Series, except Test Series 4, which will be explained later, a calibrated torque wrench was used to apply a torque to the HC. From the calibrated strain gauges, located on each of the three HC jaws, the resulting force applied due to the torque could be measured. That is, once a force was measured the torque divisor (TD) factor, i.e., force / torque, was obtained and put into the computer to convert total measured force to torque. That conversion was checked at different levels of torque but after Test 5, for most of the tests the conversion was checked at 300, 500, and 700 ft-lbf, as depicted in **Figure 46**.

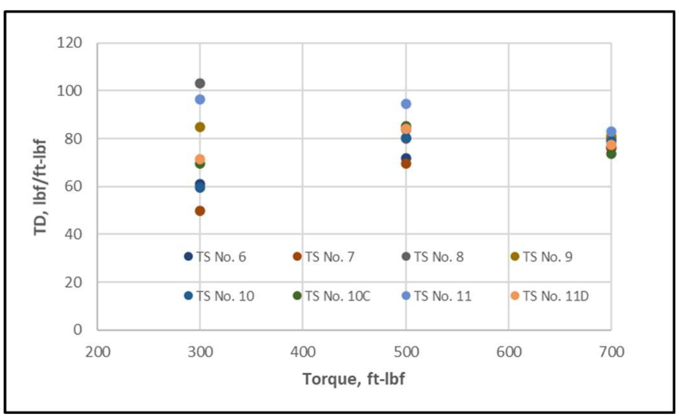


Figure 46. Torque Divisor for select tests, TS = Test Series.

[3] The tables only list selected times. The full set of data are in files, which can be found in reference [15]

As the torque increases the TD factor became more consistent, which is probably due to the fact that as more torque is applied to the HC the three jaws, and the reacting strain gauges, align and act as one unit. That is, as the force increases the three individual jaws and linkages are adjusting into place to tighten the nozzle on the installed HC gasket. Each Test Series started by checking the torque to force conversion at the different values, but it was the consistent value of TD at 700 ft-lbf that was used to convert all measured forces to torque.

An example to understand the process of setting the TD value is shown in **Table 5**. For Test 7 the adjustment began at 8:29 am and ended at 8:32 am. The data were recorded every second, but the table only shows a selected subset of those data. During those few minutes one person handled the torque wrench, another person read the torque indicator, and a third person worked with the DAS to adjust the torque indicated on the computer by adjusting the TD. During the short time period the torque was checked at 300, 500 and 700 ft-lbf. The yellow boxes in the table show values near those targets. When the torque wrench was near one of those values the TD was changed to match what was indicated to check the overall operation of the DAS. The final value set was where most tests started, that is, near 700 ft-lbf. For Test 7 that final starting value ended up being 681 ft-lbf. Making such adjustments with the 6-foot-long torque wrench while someone was reading the dial, so that the third person could manipulated the DAS to read a target value made obtaining an exact value, like 700, challenging. An exact torque value was not important. Having the computer match what was obtained from the calibrated wrench was the goal.

Table 5:Subset of Test 7 Data to Illustrate TD Adjustment Process

Test Date	Test Time (1)	Temp °C	HC Jaw 1 Force, lbf	HC Jaw 2 Force, lbf	HC Jaw 3 Force, lbf	Sum of Forces, lbf	TD lbf / ft-lbf	Torque on DAS, ft-lbf
5-Aug-21	08:29:42.59	24.42	1286.1	1577.8	1475.5	4,339.4	72	60.3
5-Aug-21	08:30:46.59	24.38	4487.5	5372.4	5264.5	15,124.4	66	229.2
5-Aug-21	08:30:50.59	24.38	4453.6	5329.1	5217.2	14,999.9	60	250.0
5-Aug-21	08:30:58.59	24.38	4405.6	5255.4	5174.6	14,835.7	50	296.7
5-Aug-21	08:31:14.60	24.37	7731.3	9071.1	9218.7	26,021.1	70	371.7
5-Aug-21	08:31:18.60	24.38	9193.4	11361.4	11244.4	31,799.3	64	496.9
5-Aug-21	08:31:22.60	24.38	10305.4	12426.4	12426.6	35,158.4	66	532.7
5-Aug-21	08:31:26.60	24.37	10899.7	11973.2	12319.6	35,192.5	68	517.5
5-Aug-21	08:31:30.60	24.39	10809.3	11740.3	12149.7	34,699.4	70	495.7
5-Aug-21	08:32:10.60	24.38	16790.2	19473.8	18622.6	54,886.6	74	741.7
5-Aug-21	08:32:15.60	24.38	17860.3	18860.3	18688.4	55,409.0	76	729.1
5-Aug-21	08:32:19.60	24.38	17510.8	18233.6	18093.2	53,837.7	80	673.0
5-Aug-21	08:32:22.60	24.37	17315.6	17974.3	17810.3	53,100.2	78	680.8

(1) For Test 7 the TD adjustment started at 08:29 am. Recording was every second, but table only shows times at which the TD was changed during the adjustment process. At the last time of 8:32:22 the adjustment finalized to a TD of 78 giving a starting torque of 681 ft-lbf.

Finally, Test 4 was unique because it was the only test started with the use of the impact wrench instead of the calibrated torque wrench. As such, it is useful to better describe the relation between the impact wrench used in HCA to torque and seal Hanford Connectors.

The following were the steps taken during Test 4.

1. A new SR gasket installed into the HC.
2. The HC placed on nozzle.
3. The outputs from strain gauges on the three HC jaws were set to zero.
4. The impact wrench was used to tighten the HC and it was stopped after 9 seconds of impacting. The computer indicated 589 ft-lbf. This value was converted from the measured applied force of 44764 lbf with the conversion factor of 76 lbf/ft-lbf that was still in the computer from the previous test.
5. To obtain the actual applied torque to the HC, the impact wrench was replaced with the calibrated toque wrench within 5 minutes.
6. Without making any changes and being careful to not add any other loading to the HC the measured toque was set at a measured value of 600 ft-lbf.
7. At 600 ft-lbf the applied force from the calibrated strain gauges was measured to be 43200 lbf, which gave a new force-to-torque factor (TD) of 72 lbf/ft-lbf.
8. With the newly obtained conversion factor, then the initially obtained force of 44764 lbf from the impact wrench imparted a torque of 44764 lbf / (72 lbf/ft-lbf) = 622 ft-lbf.

This exercise shows the conversion of torque to force is not constant and is dependent on the way the HC connector is set up, i.e., the linkages, jaw placement, lubrication, among other factors. Therefore, during each test and for each retorqueing of the HC the measured torque was compared to the measured force that was summation of the measured forces from the strain gauges installed on each of the three jaws of the HC. This enabled a revision of conversion factor for each new setup to minimize errors due to the changing relationship between force and torque. The most accurate value of applied torque for any test is exactly when torque is applied and measured. As the value of applied force and its converted torque drop through gasket relaxation the value of torque becomes more qualitative than quantitative because the conversion factor is kept constant, which it is not. However, it gives a reasonable idea of the loss of torque as the force drops, which was measured with calibrated strain gauges.

Note: Yellow highlights in following tables show where data were affected as explained in the notes on each table.

Table 6:Experimental Data Tests 1-4 in Applied Torque

Name of Test		Test 1A	Test 1B	Test 2A	Test 2B	Test 3A	Test 3B	Test 4A	Test 4B
Start Date of Test		12-May-21	13-May-21	19-May-21	20-May-21	1-Jun-21	2-Jun-21	8-Jun-21	17-Jun-21
Start of of Test		8:45:37	15:46:19	14:05:44	8:44:38	11:09:16	7:06:27	13:32:15	12:59:23
Type of Gaskets Used (1)		fresh 4-Hole	< Same	fresh SR	< Same	fresh LS-o	< Same	fresh SR	< Same
Gasket Thickness, inch (2)		0.120	< Same	0.105	< Same	0.120	< Same	0.105	< Same
Test Condition (3)		IT	RT	IT	RT	IT	RT	IT	RT
Ambient Temp. (1 Sigma), °C		21.4 (1.9)	23.0 (1.9)	24.3 (1.0)	24.0 (1.0)	23.2 (0.6)	24.0 (0.6)	24.5 (0.7)	23.7 (0.7)
Duration hour	Duration Day	Applied Torque, ft-lb							
0	0.00	1073	1024	847	849	847	802	619	651
0.083 (5 min.)	0.0035	954	1015	760	840	780	800	600	647
0.5	0.02	934	1005	734	834	747	796	563	642
1	0.04	926	999	715	813	735	792	550	638
2	0.08	917	993	670	799	724	786	540	633
4	0.17	924 (4)	998	686	781	712	778	529	627
6	0.25	926 (4)	984	677	768	704	771	523	622
8	0.33	930 (4)	980	671	756	698	764	519	617
18	0.75	928	964	657	717	682	735	507	601
24	1	924	974 (4)		708		722	504	597
48	2		966				689	493	579 (6)
72	3		957				671	487	no data (6)
96	4		950				657	482	no data (6)
120	5		938 (5)				647	478	551
144	6							476	545
168	7							475	543
192	8							473	541
216	9							471	539
240	10								536
264	11								534

Notes:
(1) SR = Snap Ring Gasket, LS-o = Lamp Shade Gasket (old style, 0.120 inch thick).
(2) All listed thickness are nominal. Actual thickness may be slightly different.
(3) IT = Initial Torque, RT = Retorque
(4) Slight increases in strain gauge values may have occurred due to fluctuations in ambient temperature.
(5) Test ended at 110 hours.
(6) Power loss during days 2-3 caused data loss. Value at 48 hours is really at 47.5 hours, when power was lost.

Table 7:Experimental Data Tests 5-8 in Applied Torque

Name of Test		**Test 5**	**Test 6A**	**Test 6B**	**Test 6C**	**Test 7**	**Test 8A**	**Test 8B**	**Test 8C**
Start Date of Test		30-Jun-21	19-Jul-21	19-Jul-21	19-Jul-21	5-Aug-21	18-Aug-21	18-Aug-21	18-Aug-21
Start of of Test		11:18:59	8:13:05	10:12:53	14:28:48	8:32:20	8:12:24	10:19:35	14:02:12
Type of Gaskets Used (1)		fresh SR	fresh SR	< Same	< Same	fresh LS-o	fresh LS-n	< Same	< Same
Gasket Thickness, inch (2)		0.105	0.120	< Same	< Same	0.120	0.150	< Same	< Same
Test Condition (3)		IT	IT	RT	RT	IT	IT	RT	RT
Ambient Temp. (1 Sigma), °C		24.6 (0.8)	23.6 (0.1)	24.9 (1.4)	25.9 (1.3)	25.1 (0.8)	25.9 (0.1)	26.1 (0.2)	26.5 (0.2)
Duration hour	Duration Day	**Applied Torque, ft-lb**							
0	0.00	696	695	700	699	681	722	676	723
0.083(5 min.)	0.0035	599	542	651	657	604	547	635	694
0.5	0.02	585	514	603	625	584	520	596	/\
1	0.04	581	498	582	615	578	509	582	
2	0.08	577	487	560	605	571	499	572	
4	0.17	572		539	594	565		561	
6	0.25	568			586	561			
8	0.33	565			581	558			
18	0.75	558			569	550			
24	1	556			565	547			
48	2	551			554	541			(4)
72	3	547			546	537			
96	4	546			540	534			
120	5	546			535	534			
144	6	545			531	531			
168	7	544			528	529			
192	8	541			524	528			
216	9	540			519	526			
240	10	538			516	525			
264	11	537			515	523			\/
288	12	536			513	521			584 (5)
312	13	535			509	521			
336	14	534			508				
360	15	534							

Notes:
(1) SR = Snap Ring Gasket, LS-o=Lamp Shade Gasket (old style, 0.120" thick), LS-n=Lamp Shade Gasket (new style, 0.150" thick).
(2) All listed thickness are nominal.
(3) IT = Initial Torque, RT = Retorque
(4) Power loss to the computer caused data loss.
(5) Test ended at 295 hours.

Table 8:Experimental Data Tests 9-10 in Applied Torque

Name of Test		**Test 9A**	**Test 9B**	**Test 9C**	**Test 10A**	**Test 10B**	**Test 10C**	**Test 10D**
Start Date of Test		9-Sep-21	13-Sep-21	14-Sep-21	6-Oct-21	7-Oct-21	12-Oct-21	12-Oct-21
Start of of Test		13:56:02	10:24:25	8:15:26	9:35:28	13:23:40	8:12:25	15:48:48
Type of Gaskets Used (1)		fresh SR + LS-n	< Same	same SR + fresh LS-n	fresh SR	< Same	same SR + fresh LS-n	< Same
Gasket Thickness, inch (2)		0.105 + 0.150	< Same	< Same	0.105	< Same	0.105 + 0.150	< Same
Test Condition (3)		IT	RT	IT	IT	RT	IT	RT
Ambient Temp. (1 Sigma), °C		21.6 (1.4)	22.1 (0.8)	22.2 (1.0)	21.7 (0.2)	21.5 (0.5)	20.0 (0.5)	19.9 (1.5)
Duration hour	Duration Day	**Applied Torque, ft-lb**						
0	0.00	713	698.1	711	691	705	721	704
0.083 (5 min.)	0.0035	633	696	577	538	693	No Data	698
0.5	0.02	623	695.3	559	523	686	No Data	689
1	0.04	619	694.6	553	520	681	588	684
2	0.08	615	693.6	547	516	674	579	677
4	0.17	611	692.2	540	512	666	573	669
6	0.25	608	691.2	537	510	661	571	664
8	0.33	606	690	534	508	658		659
18	0.75	600	682.4	524	504	649		649
24	1	599	680 (4)	520		647		646
48	2	595		513		640		634
72	3	594		509		637		627
96	4	592 (4)		508				622
120	5			506				617
144	6			505				616
168	7			503				616
192	8							616
216	9							616
240	10							617
264	11							614
288	12							614
312	13							614
336	14							611
360	15							609
384	16							610
408	17							609
432	18							608
456	19							607
480	20							607
504	21							608

Notes:
(1) SR = Snap Ring Gasket, LS-n = Lamp Shade Gasket (new style, 0.150" thick.)
0.150 inch thick.
(2) All listed thickness are nominal. Actual thickness may vary.
(3) IT = Initial Torque, RT = Retorque
(4) Test 9A ended at 93 hours and Test 9B ended at 23.5 hours.

Table 9:Experimental Data Test 11 in Applied Torque

Name of Test		Test 11A	Test 11B	Test 11C	Test 11D	Test 11E	Test 11F
Start Date of Test		3-Nov-21	4-Nov-21	9-Nov-21	9-Nov-21	9-Nov-21	11-Nov-21
Start of of Test		9:01:14	14:02:14	8:06:18	10:48:20	16:03:20	17:02:41
Type of Gaskets Used (1)		fresh SR	< Same	< Same	same SR + fresh LS-o	< Same	< Same
Gasket Thickness, inch (2)		0.105	< Same	< Same	0.105 + 0.120	< Same	< Same
Test Condition (3)		IT	RT	RT	IT	RT	RT
Ambient Temp. (1 Sigma), °C		20.0 (0.5)	20.0 (0.1)	20.1 (0.1)	21.2 (0.3)	20.9 (0.9)	20.2 (1.3)
Duration hour	Duration Day	Applied Torque, ft-lb					
0	0.00	736	665	668	705	672	672
0.083 (5 min.)	0.0035	495	646	655	587	663	665
0.5	0.02	481	631	653	566	645	653
1	0.04	476	623	652	559	632	642
2	0.08	472	615	651	552	615	629
4	0.17	469	607		543	596	613
6	0.25	466	602			585	604
8	0.33	464	599			578	597
18	0.75	458	592			562	580
24	1	457	588			556	576
48	2		581			538	567
72	3		576				562
96	4		572				559
120	5						557
144	6						554
168	7						549
192	8						545
216	9						544
240	10						543
264	11						540
288	12						539
312	13						537
336	14						537
360	15						535
384	16						535
408	17						533
432	18						533

Notes:
(1) SR = Snap Ring Gasket, LS-n = Lamp Shade Gasket (new style, 0.150" thick.)
(2) All listed thickness are nominal. Actual thickness may vary.
(3) IT = Initial Torque, RT = Retorque

Table 10:Experimental Data Test 12 in Applied Torque

Name of Test		Test 12A	Test 12B	Test 12C	Test 12D	Test 12E	Test 12F
Start Date of Test		30-Nov-21	30-Nov-21	2-Dec-21	7-Dec-21	14-Dec-21	16-Dec-21
Start of of Test		8:31:04	13:54:16	13:20:55	9:11:00	9:58:45	15:43:55
Type of Gaskets Used (1)		fresh SR	< Same	< Same	< Same	Same SR (5) + fresh DG	< Same
Gasket Thickness, inch (2)		0.105	< Same	< Same	< Same	0.105 + 0.191	< Same
Test Condition (3)		Initial Torque	RT	RT	RT	IT	RT
Ambient Temp. (1 sigma), °C		17.3 (1.4)	20.8 (0.4)	21.3 (0.7)	20.7 (0.7)	17.9 (1.7)	20.6 (1.4)
Duration hour	Duration Day	Applied Torque, ft-lb					
0	0.00	698	751	688	No Data	772	563 (6)
0.083 (5 min.)	0.0035	586	698	686	/\	520	533
0.5	0.02	559	686	681		472	498
1	0.04	552	653	678		457	384
2	0.08	545	641	671		443	468
4	0.17	538	629	661		429	450
6	0.25		622	651	(4)	431	440
8	0.33		618	641		397	432
18	0.75		607	615		367	411
24	1		605	607		361	403
48	2		593	583		344	383
72	3			570	\/		370
96	4			561	555		365
120	5				553		362
144	6				No Data		360
168	7				552		356
192	8						354
216	9						350
240	10						345
264	11						339
288	12						335
312	13						330
336	14						326
360	15						322
384	16						319
408	17						315
432	18						312

Notes:
(1) SR = Snap Ring Gasket, LS-n = Lamp Shade Gasket (new style, 0.150" thick.), DG = Double Gasket (0.190" thick)
(2) All listed thickness are nominal. Actual thickness may vary.
(3) IT = Initial Torque, RT = Retorque
(4) Power loss to the computer caused loss of data.
(5) The SR for tests 12E-12G was the same for tests 12A-12D, but the metal snap ring was removed to demonstrate differences in stress performance.
(6) The initial torque was probably larger than the 563 recorded. The DAS frequency was not changed from it previous setting of 5 minutes and in that short time and initial applied torque can drop as much as 50 ft-lbf for a retorqued connection.

Table 11:Experimental Data Test 13 in Applied Torque

Name of Test		Test 13A	Test 13B	Test 13C	Test 13D	Test 13E
Start Date of Test		4-Jan-22	6-Jan-22	11-Jan-22	11-Jan-22	13-Jan-22
Start of of Test		8:31:57	15:34:19	8:37:33	13:49:52	16:21:04
Type of Gaskets Used (1)		fresh SR	< Same	Same SR + fresh DG	< Same	< Same
Gasket Thickness, inch (2)		0.105	< Same	0.105 + 0.190	< Same	< Same
Test Condition (3)		IT	RT	IT	RT	RT
Ambient Temp. (1 Sigma), °C		18.7 (1.7)	19.6 (1.6)	17.4 (0.7)	18.3 (1.7)	18.8 (2.4)
Duration hour	Duration Day	**Applied Torque, ft-lb**				
0	0.00	698	697	725	708	689.7
0.083 (5 min.)	0.0035	655	693	637	702	689.6
0.5	0.02	645	692	629	699	689.1
1	0.04	641	691	627	697	688.8
2	0.08	637	690	624	694	688
4	0.17	634	689	622	689	687
6	0.25	632	688		686	686
8	0.33	631	687		683	684
18	0.75	626	684		674	/\
24	1	625	683		674	
48	2	622	679		665	
72	3		680			(4)
96	4		674			
120	5					
144	6					
168	7					\/
192	8					665
216	9					664
240	10					664
264	11					666 (5)
288	12					666 (5)
312	13					664
336	14					662
360	15					661
384	16					660
408	17					660
432	18					661
456	19					660
480	20					660
504	21					659
528	22					655

Notes:
(1) SR = Snap Ring Gasket, LS-n = Lamp Shade Gasket (new style, 0.150" thick.)
(2) All listed thickness are nominal. Actual thickness may vary.
(3) IT = Initial Torque, RT = Retorque
(4) Power loss to the computer caused a loss of data.
(5) Slight increases in strain gauge values may have occurred due to fluctuations in ambient temperature.

Table 12:Experimental Data Tests 1-4 in Measured Force

Name of Test		Test 1A	Test 1B	Test 2A	Test 2B	Test 3A	Test 3B	Test 4A	Test 4B
Start Date of Test		12-May-21	13-May-21	19-May-21	20-May-21	1-Jun-21	2-Jun-21	8-Jun-21	17-Jun-21
Start of of Test		8:45:37	15:46:19	14:05:44	8:44:35	11:09:16	7:06:27	13:32:15	12:59:23
Type of Gaskets Used (1)		fresh 4-Hole	< Same	fresh SR	< Same	fresh LS-o	< Same	fresh SR	< Same
Gasket Thickness, inch (2)		0.120	< Same	0.105	< Same	0.120	< Same	0.105	< Same
Test Condition (3)		IT	RT	IT	RT	IT	RT	IT	RT
Ambient Temp. (1 Sigma), °C		21.4 (1.9)	23.0 (1.9)	24.3 (1.0)	24.0 (1.0)	23.2 (0.6)	24.0 (0.6)	24.5 (0.7)	23.7 (0.7)
Duration hour	Duration Day	Sum of Measured Forces from Three Strain Gauges, lbf							
0	0.00	60,960.4	58,173.6	62,650.0	62,819.7	64,375.0	60,972.1	44,550.5	46,862.3
0.083 (5 min.)	0.0035	54,203.6	57,643.1	56,314.0	62,187.3	59,300.1	60,848.0	43,192.7	46,584.9
0.5	0.02	53,050.5	57,062.9	54,286.8	60,918.7	56,745.7	60,493.6	40,547.8	46,246.0
1	0.04	52,605.7	56,748.8	52,913.4	60,121.8	55,838.3	60,205.4	39,627.2	45,940.0
2	0.08	52,082.5	56,403.2	51,701.4	59,141.7	54,990.2	59,801.7	38,874.8	45,625.0
4	0.17	52,471.9 (4)	56,111.1	50,730.7	57,795.1	54,086.2	59,147.8	38,095.6	45,157.4
6	0.25	52,625.8 (4)	55,894.2	50,131.2	56,810.7	53,510.4	58,588.6	37,660.1	44,781.1
8	0.33	52,838.2 (4)	55,673.7	49,519.0	55,964.2	53,072.9	58,091.1	37,349.5	44,456.9
18	0.75	52,697.1	54,776.4	48,612.8	53,068.4	51,802.6	55,873.5	36,531.7	43,310.4
24	1	52,469.9	55,346.4 (4)		52,368.5		54,888.7	36,278.9	42,960.2
48	2		54,852.7				52,360.7	35,500.1	41,712.2 (6)
72	3		54,347.3				50,974.9	35,059.6	no data (6)
96	4		53,978.8				49,941.3	34,678.7	no data (6)
120	5		52,866.9 (5)				49,151.8	34,421.7	39,638.1
144	6							34,274.1	39,276.6
168	7							34,208.3	39,079.9
192	8							34,044.8	38,948.5
216	9							33,919.5	38,840.5
240	10								38,620.0
264	11								38,414.7

Notes:
(1) SR = Snap Ring Gasket, LS-o = Lamp Shade Gasket (old style, 0.120 inch thick).
(2) All listed thickness are nominal. Actual thickness may be slightly different.
(3) IT = Initial Torque, RT = Retorque
(4) Slight increases in strain gauge values may have occurred due to fluctuations in ambient temperature.
(5) Test ended at 110 hours.
(6) Power loss during days 2-3 caused data loss. Value at 48 hours is really at 47.5 hours, when power was lost.

Table 13:Experimental Data Tests 5-8 in Measured Force

Name of Test		**Test 5**	**Test 6A**	**Test 6B**	**Test 6C**	**Test 7**	**Test 8A**	**Test 8B**	**Test 8C**
Start Date of Test		30-Jun-21	19-Jul-21	19-Jul-21	19-Jul-21	5-Aug-21	18-Aug-21	18-Aug-21	18-Aug-21
Start of of Test		11:18:59	8:13:05	10:12:53	14:28:48	8:32:22	8:12:24	10:19:35	14:02:12
Type of Gaskets Used (1)		fresh SR	fresh SR	< Same	< Same	fresh LS-o	fresh LS-n	< Same	< Same
Gasket Thickness, inch (2)		0.105	0.120	< Same	< Same	0.120	0.150	< Same	< Same
Test Condition (3)		IT	IT	RT	RT	IT	IT	RT	RT
Ambient Temp. (1 Sigma), °C		24.6 (0.8)	23.6 (0.1)	24.9 (1.4)	25.9 (1.3)	25.1 (0.8)	25.9 (0.1)	26.1 (0.2)	26.5 (0.2)
Duration hour	Duration Day	**Sum of Measured Forces from Three Strain Gauges, lbf**							
0	0.00	50,111.2	50,074.4	50,403.60	50,348.80	53,100.2	57,754.7	54,026.20	57,858.90
0.083(5 min.)	0.0035	43,178.2	39,018.0	46,872.40	47,338.80	47,152.1	43,766.7	51,030.20	55,520.50
0.5	0.02	42,155.7	36,554.3	43,427.10	45,023.60	45,561.8	41,611.8	47,698.90	/\
1	0.04	41,847.7	35,827.5	41,933.20	44,304.60	45,019.9	40,706.2	46,639.80	
2	0.08	41,533.3	36,121.5	40,305.70	43,575.60	44,523.2	39,973.5	45,718.60	
4	0.17	41,167.1		38,794.40	42,738.90	44,037.6		44,894.60	
6	0.25	40,928.4			42,208.90	43,763.3			
8	0.33	70,743.6			41,864.60	43,560.5			
18	0.75	40,196.3			40,966.10	42,903.6			
24	1	40,025.3			40,679.80	42,659.0			
48	2	39,642.2			39,854.00	42,180.8			(4)
72	3	39,406.0			39,317.70	41,853.7			
96	4	39,319.5			38,848.20	41,658.3			
120	5	39,309.3			38,537.00	41,617.9			
144	6	39,225.3			38,259.10	41,430.5			
168	7	39,174.9			38,039.90	41,236.2			
192	8	38,974.1			37,722.60	41,197.0			
216	9	38,464.9			37,363	41,059.0			
240	10	38,749.4			37,145.90	40,930.2			
264	11	38,674.5			36,968.30	40,816.1			\/
288	12	38,592.5			36,806.60	40,703.6			46,717.9 (5)
312	13	38,502.4			36,601.80	40,659.8			
336	14	38,438.4			36,517.00				
360	15	38,450.9							

Notes:
(1) SR = Snap Ring Gasket, LS-o=Lamp Shade Gasket (old style, 0.120" thick), LS-n=Lamp Shade Gasket (new style, 0.150" thick).
(2) All listed thickness are nominal.
(3) IT = Initial Torque, RT = Retorque
(4) Power loss to the computer caused data loss.
(5) Test ended at 295 hours.

Table 14:Experimental Data Tests 9-10 in Measured Force

Name of Test		Test 9A	Test 9B	Test 9C	Test 10A	Test 10B	Test 10C	Test 10D
Start Date of Test		9-Sep-21	13-Sep-21	14-Sep-21	6-Oct-21	7-Oct-21	12-Oct-21	12-Oct-21
Start of of Test		13:56:02	10:24:25	8:15:26	9:35:28	13:23:40	8:12:25	15:48:48
Type of Gaskets Used (1)		fresh SR + LS-n	< Same	same SR + fresh LS-n	fresh SR	< Same	same SR + fresh LS-n	< Same
Gasket Thickness, inch (2)		0.105 + 0.150	< Same	< Same	0.105	< Same	0.105 + 0.150	< Same
Test Condition (3)		IT	RT	IT	IT	RT	IT	RT
Ambient Temp. (1 Sigma), °C		21.6 (1.4)	22.1 (0.8)	22.2 (1.0)	21.7 (0.2)	21.5 (0.5)	20.0 (0.5)	19.9 (1.5)
Duration hour	Duration Day	Applied Torque, ft-lb						
0	0.00	57,017.1	55,848.2	56,154.7	55,319.3	56,396.9	57,714.2	54,925.20
0.083 (5 min.)	0.0035	50,614.8	55,727.1	46,195.4	43,070.9	55,457.1	No Data	54,442.00
0.5	0.02	49,861.0	55,620.7	44,728.5	41,881.9	54,879.8	No Data	53,726.40
1	0.04	49,534.3	55,564.9	44,235.0	41,601.4	54,467.8	45,835.9	53,318.30
2	0.08	49,225.5	55,487.7	43,729.4	41,290.7	53,917.9	45,128.0	52,816.70
4	0.17	49,919.8	55,380.3	43,233.8	40,989.2	53,279.8	44,732.9	52,184.20
6	0.25	48,672.4	55,296.6	42,938.3	40,803.5	52,903.6	44.528.8	51,764.30
8	0.33	48,493.4	55,198.5	42,723.5	40,669.4	52,634.5		51,444.70
18	0.75	47,993.6	54,589.1	41,966.8	40,281.3	51,948.5		50,632.60
24	1	47,902.3	54,397.2 (4)	41,595.1		51,746.7		50,408.60
48	2	47,638.0		41,072.0		51,238.6		49,475.50
72	3	47,531.8		40,754.5		50,980.5		48,898.20
96	4	47,374.8 (4)		40,637.2				48,534.50
120	5			40,512.5				48,115.20
144	6			40,414.5				48,029.80
168	7			40,259.4				48,053.00
192	8							48,017.90
216	9							48,064.90
240	10							48,124.40
264	11							47,927.90
288	12							47,875.20
312	13							47,893.40
336	14							47,629.80
360	15							47,504.20
384	16							47,554.40
408	17							47,409.60
432	18							47,410.80
456	19							47,396.50
480	20							47,383.90
504	21							47,390.50

Notes:
(1) SR = Snap Ring Gasket, LS-n = Lamp Shade Gasket (new style, 0.150" thick.)
0.150 inch thick.
(2) All listed thickness are nominal. Actual thickness may vary.
(3) IT = Initial Torque, RT = Retorque
(4) Test 9A ended at 93 hours and Test 9B ended at 23.5 hours.

Table 15:Experimental Data Test 11 in Measured Force

Name of Test		Test 11A	Test 11B	Test 11C	Test 11D	Test 11E	Test 11F
Start Date of Test		3-Nov-21	4-Nov-21	9-Nov-21	9-Nov-21	9-Nov-21	11-Nov-21
Start of of Test		9:01:14	14:02:14	8:06:18	10:48:20	16:03:20	17:02:41
Type of Gaskets Used (1)		fresh SR	< Same	< Same	same SR + fresh LS-o	< Same	< Same
Gasket Thickness, inch (2)		0.105	< Same	< Same	0.105 + 0.120	< Same	< Same
Test Condition (3)		IT	RT	RT	IT	RT	RT
Ambient Temp. (1 Sigma), °C		20.0 (0.5)	20.0 (0.1)	20.1 (0.1)	21.2 (0.3)	20.9 (0.9)	20.2 (1.3)
Duration hour	Duration Day	Applied Torque, ft-lb					
0	0.00	60,354.9	54,539.9	54,806.0	57,139.4	54,454.3	54,402.0
0.083 (5 min.)	0.0035	40,640.0	52,950.7	53,733.7	47,582.7	53,739.5	53,849.6
0.5	0.02	40,465.0	51,763.3	53,612.2	45,871.5	52,208.7	52,868.2
1	0.04	39,047.4	51,072.7	53,513.1	45,308.3	51,176.7	52,038.0
2	0.08	38,740.7	50,411.6	53,383.2	44,687.7	49,832.6	50,972.2
4	0.17	38,425.8	49,763.7		44,009.2	48,292.0	49,683.0
6	0.25	38,216.4	49,383.3			47,407.1	48,911.2
8	0.33	38,057.3	49,123.4			46,831.8	48,375.0
18	0.75	37,590.1	48,411.3			45,498.2	47,016.5
24	1	37,451.5	48,183.7			45,048.4	46,646.5
48	2		47,609.5			43,585.5	45,903.7
72	3		47,210.4				45,547.4
96	4		46,933.1				45,289.1
120	5						45,142.7
144	6						44,842.8
168	7						44,494.6
192	8						44,143.4
216	9						44,082.1
240	10						43,983.0
264	11						43,706.6
288	12						43,621.3
312	13						43,533.1
336	14						43,530.8
360	15						43,344.9
384	16						43,305.1
408	17						43,198.5
432	18						43,178.9

Notes:
(1) SR = Snap Ring Gasket, LS-n = Lamp Shade Gasket (new style, 0.150" thick.)
(2) All listed thickness are nominal. Actual thickness may vary.
(3) IT = Initial Torque, RT = Retorque

Table 16:Experimental Data Test 12 in Measured Force

Name of Test		Test 12A	Test 12B	Test 12C	Test 12D	Test 12E	Test 12F
Start Date of Test		30-Nov-21	30-Nov-21	2-Dec-21	7-Dec-21	14-Dec-21	16-Dec-21
Start of of Test		8:31:04	13:54:16	13:20:55	9:11:00	9:58:45	15:43:55
Type of Gaskets Used (1)		fresh SR	< Same	< Same	< Same	Same SR (5) + fresh DG	< Same
Gasket Thickness, inch (2)		0.105	< Same	< Same	< Same	0.105 + 0.191	< Same
Test Condition (3)		Initial Torque	RT	RT	RT	IT	RT
Ambient Temp. (1 sigma), °C		17.3 (1.4)	20.8 (0.4)	21.3 (0.7)	20.7 (0.7)	17.9 (1.7)	20.6 (1.4)
Duration hour	Duration Day	Applied Torque, ft-lb					
0	0.00	51,677.1	55,556.8	50,894.5	No Data	38,595.0	31,533.5 (6)
0.083 (5 min.)	0.0035	43,214.0	51,660.8	50,779.6	/\	28,600.0	29,870.7
0.5	0.02	41,329.5	50,748.3	50,415.1		26,427.2	17,907.6
1	0.04	40,874.6	48,330.6	50,156.8		25,603.8	27,049.2
2	0.08	40,326.9	47,463.5	49,684.1		24,813.4	26,189.5
4	0.17	39,828.5	46,579.2	48,925.0		23,998.2	25,224.5
6	0.25		46,057.1	48,164.0	(4)	24,119.9	24,660.0
8	0.33		45,719.9	47,443.3		22,237.8	24,232.5
18	0.75		44,922.3	45,559.9		20,561.8	23,029.7
24	1		44,736.1	44,924.1		20,219.4	22,574.6
48	2		43,902.0	43,106.0		19,274.6	21,487.5
72	3			42,167.3	\/		20,736.4
96	4			41,498.7	41,065.1		20,430.4
120	5				40,957.8		20,289.7
144	6				No Data		20,137.8
168	7				40,861.8		19,925.9
192	8						19,796.4
216	9						19,626.6
240	10						19,326.1
264	11						19,003.3
288	12						18,750.8
312	13						18,507.8
336	14						18,260.2
360	15						18,048.4
384	16						17,891.4
408	17						17,637.5
432	18						17,484.2

Notes:
(1) SR = Snap Ring Gasket, LS-n = Lamp Shade Gasket (new style, 0.150" thick.), DG = Double Gasket (0.190" thick)
(2) All listed thickness are nominal. Actual thickness may vary.
(3) IT = Initial Torque, RT = Retorque
(4) Power loss to the computer caused loss of data.
(5) The SR for tests 12E-12G was the same for tests 12A-12D, but the metal snap ring was removed to demonstrate differences in stress performance.
(6) The force was probably larger than the 31534 lbf recorded. The DAS frequency was not changed from it previous setting of 5 minutes and in that short time and initial applied force can significantly.

Table 17:Experimental Data Test 13 in Measured Force

Name of Test		Test 13A	Test 13B	Test 13C	Test 13D	Test 13E
Start Date of Test		4-Jan-22	6-Jan-22	11-Jan-22	11-Jan-22	13-Jan-22
Start of of Test		8:31:57	15:34:19	8:37:33	13:49:52	16:21:04
Type of Gaskets Used (1)		fresh SR	< Same	Same SR + fresh DG	< Same	< Same
Gasket Thickness, inch (2)		0.105	< Same	0.105 + 0.190	< Same	< Same
Test Condition (3)		IT	RT	IT	RT	RT
Ambient Temp. (1 Sigma), °C		18.7 (1.7)	19.6 (1.6)	17.4 (0.7)	18.3 (1.7)	18.8 (2.4)
Duration hour	Duration Day	**Applied Torque, ft-lb**				
0	0.00	57,964.7	57,831.9	60,506.2	58,749.9	57,248.5
0.083 (5 min.)	0.0035	54,356.0	57,496.3	53,344.0	58,314.0	57,234.9
0.5	0.02	53,570.3	57,416.5	52,210.4	58,049.1	57,198.0
1	0.04	53,224.3	57,367.0	52,005.8	57,856.9	57,169.4
2	0.08	52,914.8	57,299.4	52,005.8	57,577.3	57,118.0
4	0.17	52,625.0	57,209.1	51,638.8	57,220.9	57,006.8
6	0.25	52,457.4	57,124.0		56,924.2	56,901.6
8	0.33	52,348.7	57,047.0		56,669.3	56,802.7
18	0.75	51,927.2	56,731.1		55,980.8	/\
24	1	51,856.8	56,710.0		55,947.9	
48	2	51,598.1	56,392.8		55,159.1	
72	3		56,446.2			(4)
96	4		55,901.6			
120	5					
144	6					
168	7					\/
192	8					55,185.7
216	9					55,096.0
240	10					55,139.0
264	11					55,258.2 (5)
288	12					55,256.7 (5)
312	13					55,085.7
336	14					54,919.1
360	15					54,824.9
384	16					54,787.0
408	17					54,778.8
432	18					54,849.1
456	19					54,820.4
480	20					54,803.9
504	21					54,699.4
528	22					54,362.6

Notes:
(1) SR = Snap Ring Gasket, LS-n = Lamp Shade Gasket (new style, 0.150" thick.)
(2) All listed thickness are nominal. Actual thickness may vary.
(3) IT = Initial Torque, RT = Retorque
(4) Power loss to the computer caused a loss of data.
(5) Slight increases in strain gauge values may have occurred due to fluctuations in ambient temperature.

Appendix B. Measurement and Test Equipment

The list of measurement and test equipment was shown in **Table 3**. Each of those instruments were calibrated. For most of them that information can be found in the Measurement & Test Equipment (M&TE) System. The temperature and pressure calibrations are located in the SRNL M&TE system, and the torque wrench calibration can be found in the SRNS M&TE system. The strain gauges are separate devices and are generally intended for a single application, so they are not issued M&TE numbers. The calibration data for the strain gauges are contained in this appendix.

The two principal instruments used for measurement were the torque wrench, to obtain torque, and the strain gauges, to obtain force applied to the HC.

<u>Torque Wrench</u>

The Snap-On Tool Corp. torque wrench was 80 inches long and it was calibrated over its full range to 1500 ft-lbf in intervals of 25 ft-lbf, **Figure 47**. It was used to adjust the Torque Divisor Factor (TD) in the Data Acquisition System (DAS) so that the measured forces from the strain gauges were converted to a torque value that could be recorded. That is, the factor was adjusted until the computer output of torque matched what was read off the torque wrench dial. When the test started the DAS recorded both the forces from the three strain gauges installed on each of the three HC jaws as well as the TD and the torque.

Figure 47: Dial on Torque Wrench Utilized

<u>Strain Gauges</u>

A strain gauge [19] is composed of a very small diameter wire in which its electrical resistance changes when mechanical strain occurs. That is, increasing the length of the wire exposed to a strain (through a back-and-forth pattern) increases the sensitivity of the output. As the wire is stretched, the resistance goes up, and this change can be correlated with strain on the wire in inches/inch. Using measurement of strain of a structural member, the stress can then be calculated in the member. With stress determined, the force applied to the member can be calculated. For this experiment the axial forces were then determined in the jaws and their change with time in terms of an initial applied torque.

The strain gauges described in **Table 3** were installed on the Jaws [14] to measure strain. Consultations with Micro Measurements™ (Strain Gauge Vendor) led to the installation of strain gauges on the top of the jaws as has shown below in **Figure 48**.

Figure 48: Typical Installation of Strain Gauges on Jaws

The location was chosen to maximize the sensitivity of the strain gauges to load applied because it was the smallest cross-sectional area available that provided sufficient room to install the strain gauges. The area below the strain gauge (Jaw substrate) was sanded to a smooth finish, then prepared for gauge installation following the vendor's directions for cleaning the surface (multi-step process). Once cleaned, the strain gauges were installed on both sides of the jaws.

To measure purely axial loading (no bending or shear loading), the Poisson Tension Cell was chosen for the installation of the strain gauges. The four legs of a Wheatstone Bridge represent a resistance associated with strain, either longitudinally or normal to the longitude direction (Poisson's Ratio), as shown below in **Figure 49**.

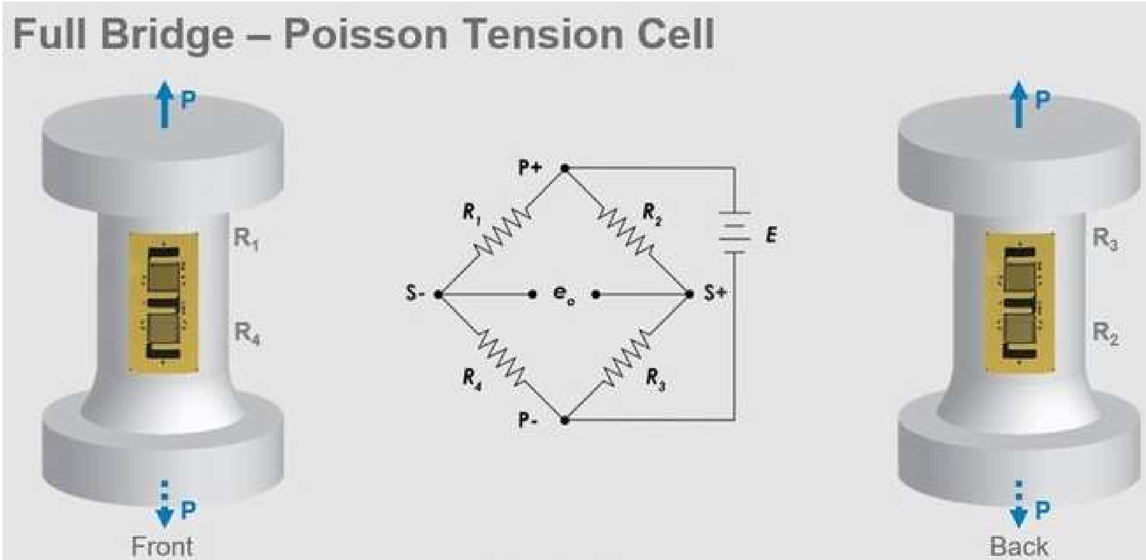


Figure 49: Poisson Tension Cell

There are a few ways to use a Wheatstone Bridge, including 1/4 Bridge, 1/2 Bridge, and a full Bridge. The easiest installation is using a 1/4 Bridge. Increasing the use of strain gauges (legs) of a Wheatstone Bridge improves sensitivity and decreases thermal effects on wiring. A 1/2 Bridge provides twice the output voltage per unit resistance as a 1/4 Bridge, and a Full Bridge improves that output to 2.6 times a 1/4 Bridge, while providing temperature compensation of the wiring and lead resistance of the wiring. Consequently, the advantages of a Full (4 leg) Wheatstone Bridge installation are minimization of temperature affects, and a maximization of sensitivity to strain. A Full (4 leg) Wheatstone Bridge was chosen for this application. The completed installation is shown below in **Figure 50**.

Figure 50: Completed Hanford Connector Installation with Included Strain Gauges

The measured value of strain in each Jaw can be related to stress by the following equation:

$$\sigma = E \bullet \varepsilon,$$

where σ is the resulting stress, E is the Modulus of Elasticity (a characteristic of the material), and ε is the strain (in non-dimensional inches/inch). With the resulting stress, the load in the jaw can then be calculated by the following equation for stress resulting from axial loading:

$$\sigma = P / A,$$

where P is the load applied axially, and A is the cross-sectional area. The cross-sectional area was measured, and consequently the load in the jaw could then be determined. The Modulus of Elasticity was determined from Reference [14] for 410 Stainless Steel.

The strain gauges, once installed on the jaws, were calibrated as shown below.

After the HC jaws were instrumented with the strain gauges the jaws were placed in a calibrated tensile tester. The tester M&TE No. LP5-504 (9/5/2021) was calibrated by MTS Systems Corporation on 9/5/2019. The arrangement is shown **Figure 51**.

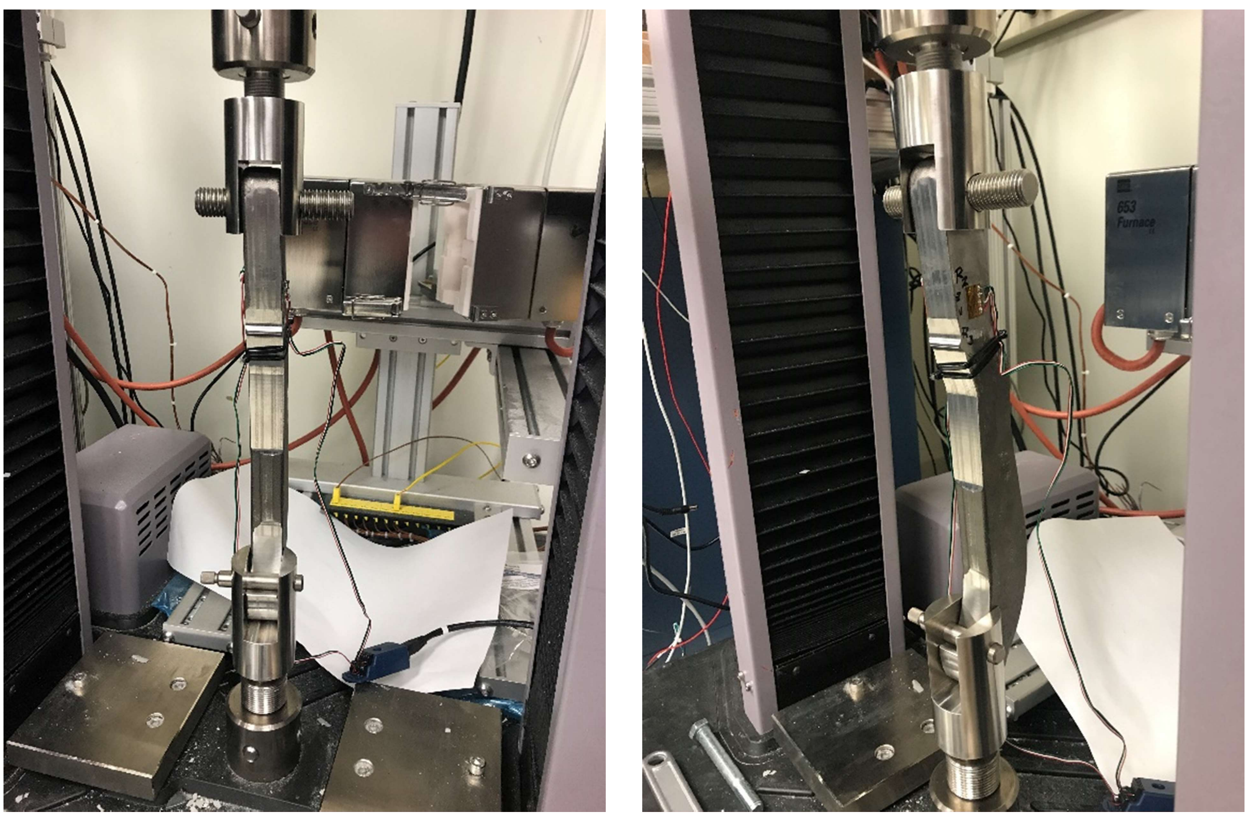


Figure 51: Jaw Calibration Set Up

Therefore, the output from the installed strain gauges were recorded and calibrated against the measured force obtained from the tensile tester. That is, the force was applied to the tensile tester and the output from the strain gauges were measured to develop correction curves so the output from the strain gauges could be related to accurate applied forces. Those data are shown in Table 18, Table 19, Table 20, and Table 21.

Table 18:Strain Gauge Calibration Data (Table 1 of 4)

Nominal Applied Load, lbs	Actual Applied Load, lbs	Indicated on DAS, lbs					
						1000	1000
						11000	11000
2000	1980	1786					
4000	3963	3539					
5000	4965	4426					
6000	5307	5960					
8000	7072	7949					
10000	8850	9943					
11000	9745	10950					

SF=1.123 Iterated True Load=SF X DAS Indicated Load

ReCalibration with SF=1.123

Nominal Applied Load	Actual Applied Load	Indicated on DAS
1000	1074	1017
3000	3033	2990
5000	5120	5092
7000	7058	7044
9000	9047	9045
11000	10904	10910

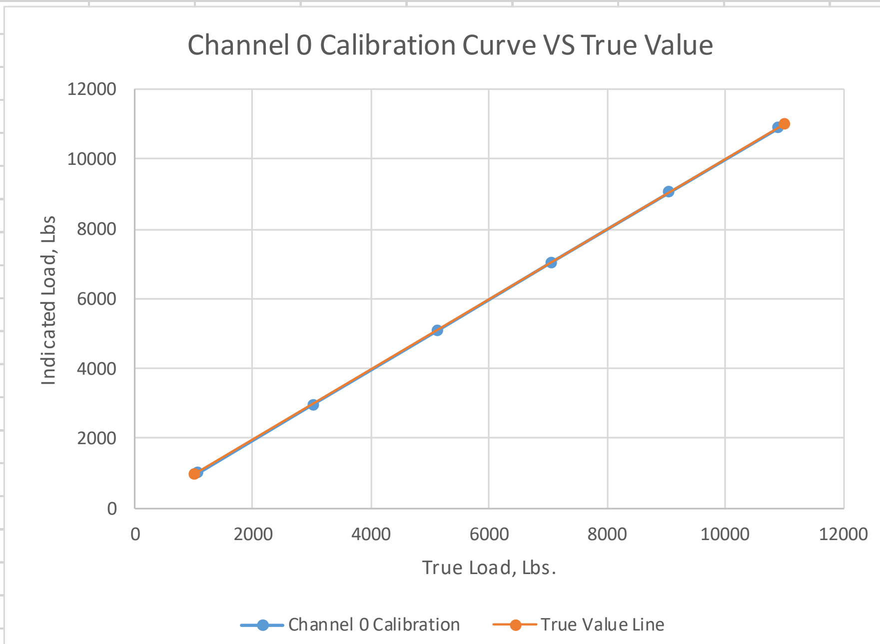


Table 19: Strain Gauge Calibration Data (Table 2 of 4)

Nominal Applied Load, lbs	Actual Applied Load, lbs	Indicated on DAS, lbs
2000	1987	1612
4000	3988	3241
5000	5987	4887
6000	7986	6551
8000	9981	8217
10000	10985	9061

1000	1000
11000	11000

SF=1.212 Iterated True Load=SF X DAS Indicated Load

ReCalibration with SF=1.212

Nominal Applied Load	Actual Applied Load	Indicated on DAS
1000	992	999
3000	3032	3023
5000	4936	4920
7000	7088	7073
9000	8884	8836
11000	10954	10948

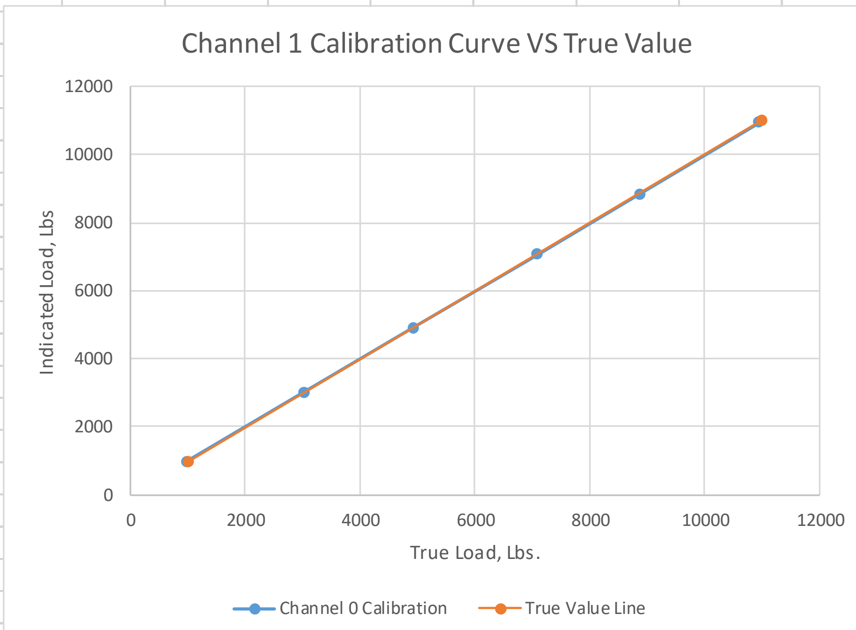


Table 20: Strain Gauge Calibration Data (Table 3 of 4)

Nominal Applied Load, lbs	Actual Applied Load, lbs	Indicated on DAS, lbs		
			1000	1000
			11000	11000
2000	1986	1617		
4000	3993	3275		
5000	5991	4941		
6000	7980	6615		
8000	9978	8319		
10000	10981	9178		

SF=1.1970 Iterated True Load=SF X DAS Indicated Load

ReCalibration with SF=1.1970

Nominal Applied Load	Actual Applied Load	Indicated on DAS
1000	1037	1073
3000	3015	3023
5000	5045	5034
7000	7055	7042
9000	8945	8939
11000	10960	10956

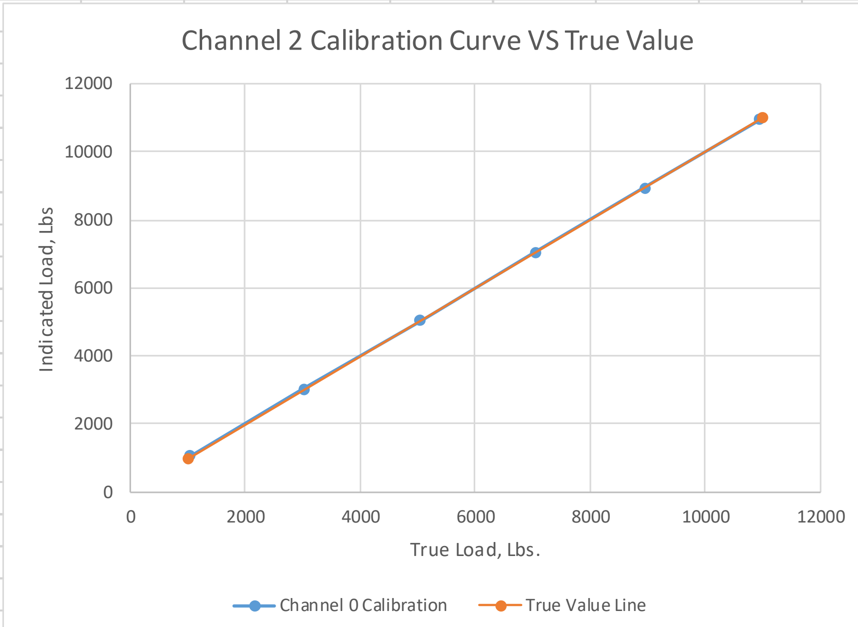


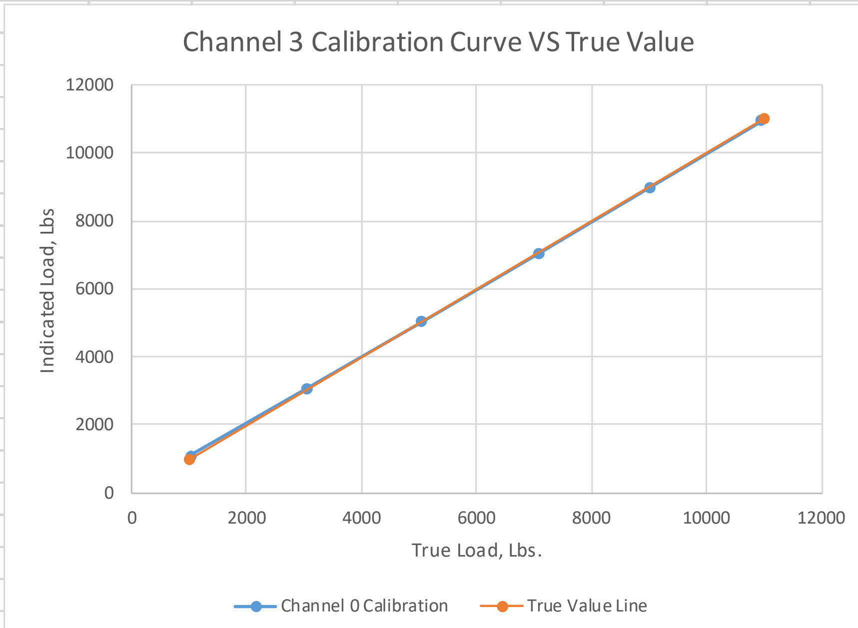
Table 21: Strain Gauge Calibration Data (Table 4 of 4)

Nominal Applied Load, lbs	Actual Applied Load, lbs	Indicated on DAS, lbs				
					1000	1000
					11000	11000
2000	1988	1584				
4000	3990	3200				
5000	5993	4834				
6000	7990	6485				
8000	9991	8155				
10000	10987	8991				

SF=1.222 Iterated   True Load=SF X DAS Indicated Load

ReCalibration with SF=1.222

Nominal Applied Load	Actual Applied Load	Indicated on DAS
1000	1028	1092
3000	3064	3081
5000	5043	5025
7000	7086	7057
9000	9020	8995
11000	10953	10950



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