Restore-L Satellite Servicing Internship Final Report

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Nomenclature

PTS	=	Propellant Transfer Subsystem
HMA	=	Hose Management Assembly
NASA	=	National Aeronautics and Space Administration
EDU	=	Engineering Development Unit
EDO	=	Engineering Development & Operations
NIFS	=	NASA Interns, Fellows, and Scholars
PMMA	=	polymethyl methacrylate

Abstract

An experiment was conducted to determine whether a sample of shorter flexible metal hoses could sustain tensile loads of up to 200 lbf and continue to meet the minimum mission requirements. The purpose of this experiment was to determine if tension loads during the processing of the hoses compromise performance. With this information, it will be decided whether the flight flex-hose manufacturer should proceed with the testing of the full-scale flex-hoses. To reduce the time and funding required for this test, a test fixture was designed and assembled in the Engineering Development & Operations (EDO) test facility. In this test fixture, two Engineering Development Unit (EDU) flex-hoses were loaded with free floating weights up to 350 lbf. A load of 200 lbf equates to the maximum expected loading with a margin of safety, thus all data recorded after 200 lbf was purely for reference. Measurements were taken using a tape measure and a custom datum measurement system to record the loaded and unloaded length of each flex-hose at various loads. Any permanent stretching beyond a 1/8th of an inch was indicative of inelastic yielding. The loading of each flex-hose was done with an initial weight 80 lbf and was increased to 100 lbf. Additional loading up to 350 lbf was done by 50 lbf increments thereafter.

During the performance of the test, slippage occurred in the mounting of the flex-hoses in the test fixture. The first slippage occurred during the testing of the first flex-hose due to the collar of the flex-hose slipping within the collet of the top Kellem. As a result, the first flex-hose test was terminated early to modify the fixture. Due to the flex-hose not inelastically yielding, the test was repeated on the first flex hose. This test resulted in another instance of slippage in the upper collar of the Kellem due to tape interfering with the securing of a collet around the collar of the flex-hose. The test was then continued with one more slippage of the flex-hose within the collet of the bottom Kellem. Preventive measures were taken for future slippage, and the second hose remained secure during testing.

Once the tests were concluded, the elongation of each hose was analyzed for inelastic yielding. Both flex-hoses stretched a measurable and repeatable amount under loading, however, this stretching was recovered once each hose was unloaded. As a result, both EDU flex-hoses did not experience any inelastic yielding during the tension testing. Once received, one additional flex-hose will be tested for yielding, but at the time of this paper, the recommendation is to proceed with testing of the full-scale flex-hoses at the flex-hose manufacturer.

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I. Introduction

Satellites in space have a limited amount of fuel that can be used before they must be decommissioned. The goal of the Restore-L project is to refuel satellites in orbit and prolong their lifespan for many years to come. In addition, technologies developed from this project will be transferred to commercial entities to help create a new domestic servicing industry.

In support of this goal, the Propellant Transfer Subsystem (PTS) and Hose Management Assembly (HMA) must meet the requirements needed to successfully complete the mission. As a result, there must be testing of possible scenarios that may impact the functioning of the PTS and HMA systems during pre-launch ground testing and on-orbit. One instance is the possible plastic deformation of the flight flex-hoses due to tension stress during standard ground processing operations by the National Aeronautics and Space Administration (NASA).

With the possibility of this outcome, an experiment was designed to test the effect of tension stresses on Engineering Development Unit (EDU) flex-hoses. These EDU flex-hoses had a much shorter length of 36 inches in comparison to the actual flight flex-hoses that will be used on-orbit. Despite this shorter length, these “shortie” hoses had the same welded joints as the flight flex-hoses, only in a more condensed fashion. Therefore, the tensile test results of these EDU hoses were used to determine if standard ground processing operations would prevent the flight flex-hoses from meeting the mission requirements.

II. Tension Test

A. Preliminary EDU Flex-Hose Inspection

Initially, each EDU flex-hose was inspected for manufacturing imperfections from the flex-hose manufacturer. Furthermore, the tension test could result in the hose yielding and, therefore, any imperfections could influence the test. The scrutinizing of these hoses led to the discovery of slight separation in portions of the stainless steel inner braiding, and errors in the weaving of the braiding. These sites were marked with green tape. Orange tape was used to segment the inspection, as seen in Fig. 1.

Figure 1. EDU flex-hose with imperfections marked in green. Image credit: Brian Nufer, NIFS mentor.

B. Design and Construction of Tension Test Fixture

A testing fixture was designed and built in the Engineering Development & Operations (EDO) test facility to vertically hang each EDU flex-hose with weights. To reduce the time and funding required for this test, a testing fixture was assembled out of miscellaneous items (stepladder, foam insulation, and wood) in the EDO. A wooden platform made from plywood was built as a means of transferring the weight of the platform itself and the weights to the EDU flex-hose. The platform was threaded with rope and wrapped around a c-clamp to support the load. In addition, the c-clamp was pinned through a Kellem that was attached to the lower collar of the EDU flex-hose, as seen in Fig. 2. As a result, the total weight of the platform and weights is distributed to the flex-hose in the form of a total hanging load, as shown in Fig. 3. In addition to the wooden platform, a metal bar is used to support the top Kellum, and effectively the flex-hose from the top of the stepladder.

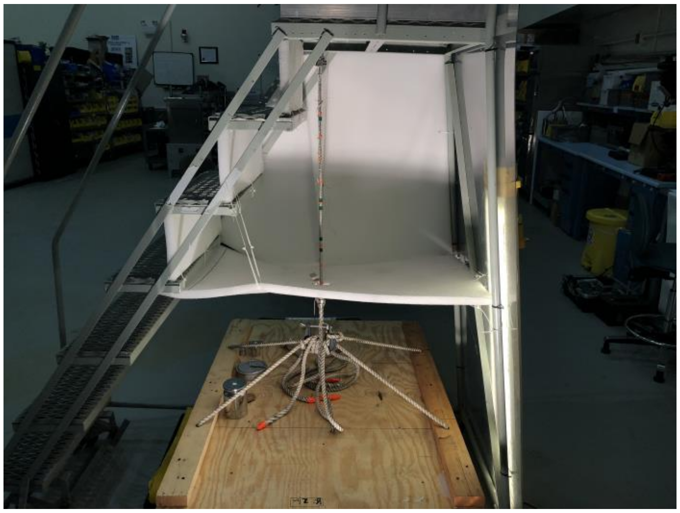

Figure 2. Tension Test Setup. Image credit: Brian Nufer, NIFS mentor.

Figure 3. Maximum load configuration. Image credit: Brian Nufer, NIFS mentor.

Furthermore, when the EDU flex-hose is loaded in tension, the hose could plastically yield until the strands fracture and cause the hose to fail by splitting in half. During this failure, the hose could recoil and whip people in the surrounding area. Due to this possibility, foam panels were installed on the stairs of the step ladder and on one side for safety during the test. Another safety precaution consisted of a horizontal guard for the hose to be fed through, such that if the hose failed during loading of the wooden platform, the person loading the platform would be safe. In addition, the back of the step ladder was covered with a thin sheet of polymethyl methacrylate (PMMA) for protection. Therefore, only one exterior side would be exposed for video recording purposes.

C. Test Procedure

The goal of the test was to verify no significant stretching of the hose indicative of inelastic yielding at a weight of 200 lbf or less. A benchmark of 200 lbf was determined to simulate maximum operating conditions with a factor of safety margin. All other data for tests at above 200 lbf are for reference only. For a given EDU flex-hose, the applied load was initially set at 80 lbf by hanging the weight of the platform itself (62.2 lbf) and placing several weights on this platform. Next, the loading of the flex-hose was increased by 20 lbf for a total weight of 100 lbf. Once a weight of 100 lbf was achieved, the loading was increased by 50 lbf thereafter to a maximum load of 350 lbf. The maximum loading configuration can be seen in Fig. 3.

Figure 4. Datum reference. Image credit: Joseph Dziekan, NIFS intern.

At each loading, the length of the hose was measured using two different methods before the load was removed. One of the methods involved using a tape measure to measure the distance from collar to collar of the flex-hoses to the nearest 1/16th inch. The second method involved using tape as a datum attached to a string parallel to the hose, to measure its length with a ruler to the nearest 1/32nd inch. The tape around the string is initially level with the collar before loading as seen in Fig. 4. The datum string is fastened with similar string tied around the flex-hose for the full length of the hose with the bottom being free. A knot and loop of a separate string is tied every 2 inches down the length of the flex-hose to ensure the string remains parallel to the hose. Once the hose is loaded, the static string attached parallel to the flex-hose will remain stationary as the hose elongates. The displacement between the tape and the collar of the flex-hose can then be used to measure the elongation of the hose during the test.

Once the load was removed, the length of the hose was measured again using the same two methods. This continued for every loading until 350 lbf was achieved. Due to the expected elastic elongation of the hose, any permanent elongation of the hose farther than a 1/8th of an inch was considered inelastic yielding. Similarly, this process was repeated for one other hose.

III. Results

A. Testing of First Hose (Run 1)

The loading and length measurements for the first hose during testing are summarized in Table 1 below. The EDU flex-hose data are limited for run 1 of the first hose due to a misinterpretation of the testing procedure. This resulted in no data collection of the loaded length of the flex-hose using either measuring method. In addition, the test was terminated early after the top Kellem slipped and shock loaded the hose at 150 lbf. Furthermore, a maximum unloaded length of 31.875 inches was achieved at a load of 80 lbf.

Table 1. Length measurements of first EDU flex-hose under different loads for run 1

Weight, lbf	Unloaded Length Tape Measure, in	Unloaded Length Tape Datum, in
0	31.75	N/A
80	31.875	0.1875
100	31.8125	0.1875
150	31.75	0.1875

The overall unloaded length of the first EDU flex-hose using the tape measure was consistently around 31.8125 inches +/- 1/16th of an inch. In addition, the accuracy of the given tape measure is to the nearest 1/16th of an inch. As a result, the variation of these unloaded length measurements can be explained by the inherent variability in the measuring device. Therefore, the measurements taken do not indicate the flex-hose experienced any inelastic yielding.

In addition, the shock loading of the flex-hose due to slippage in the Kellem collet was analyzed for future prevention. Each steel Kellem used to grip the collar of the flex-hose works by having four identical quarter-round pieces that can be secured around a shaft or collar with a hose clamp in the manner shown in Fig. 5. As seen in Fig. 6, the individual quarter-round pieces have three different radii going along the length of the piece. During testing, the collar of the flex-hose was resting near the fillet at location 1 of Fig. 6. Once a loading of 150 lbf was applied, the collar of the flex-hose made contact with the fillet. The radius of the collar was smaller than the cut Kellem piece both at locations 1 and 2 of Fig. 6, resulting in the collar slipping down to make contact with the edge at location 2.

Figure 5. Installed configuration of Kellem. Image credit: Joseph Dziekan, NIFS intern.

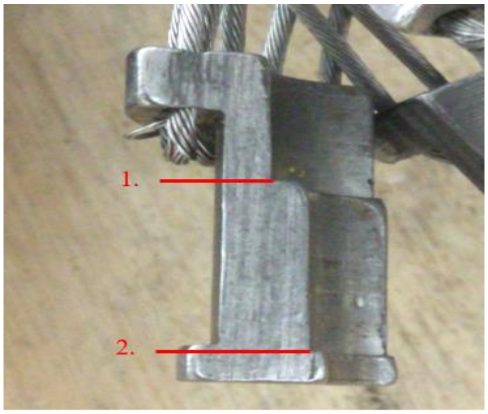

Figure 6. Individual section of Kellem. Image credit: Joseph Dziekan, NIFS intern.

Furthermore, the initial placement of the flex-hose's collar in the Kellem can be seen in Fig. 7. This orientation of the collar in the Kellem is at the largest of the three radii of each quarter-round piece. As previously mentioned, the collar then slipped from the location shown in Fig. 7, to the location shown in Fig. 8. The radius below the collar of the hose in Fig. 8 is the smallest radius of each quarter-round piece. Therefore, the Kellem slipped and was caught by the ledge formed due to the reduction in the radius. As a result, the flex-hose was shock loaded and it was decided to terminate the test early.

Figure 7. Position of collar in Kellem initially. Image credit: Joseph Dziekan, NIFS intern.

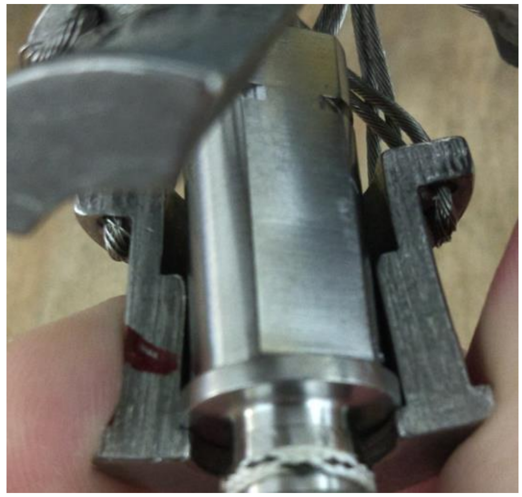

Figure 8. Position of collar in Kellem after slippage. Image credit: Joseph Dziekan, NIFS intern.

B. Testing of First Hose (Run 2)

Once the test fixture was adjusted after run 1, the test was repeated to the maximum loading of 350 lbf as previously described. During this run, data was collected for both methods of measuring length, including unloaded and loaded lengths. Slippage occurred at 150 lbf due to using tape to mount the tape datum measurement system to the upper collar of the flex-hose. The Kellem collet had a looser grip on the upper collar of the EDU flex-hose due to the tape, resulting in the collet slipping. In consequence, the subsequent length measurements using the datum measurement system were invalidated and thus these data are omitted from this report (the appendix contains these extraneous data). However, the data collected from the tape measure remained consistent and unaffected by the slippage in the collar. For subsequent tests, the tape datum measurement system was secured via the tightening of the Kellem collet around the upper collar. The summarization of this test data can be seen in Table 2.

Table 2. Length measurements of first EDU flex-hose under different loads for run 2

Weight, lbf	Loaded Length Tape Measure, in	Unloaded Length Tape Measure, in
0	N/A	31.875
80	31.875	31.813
100	31.875	31.813
150	31.938	31.813
200	31.938	31.750
250	32.000	31.750
300	31.938	31.750
350	31.938	31.813

After the loading reached 250 lbf, the bottom Kellem attached to the EDU flex-hose slipped and shock loaded the hose. The bottom Kellem was misaligned causing the collet to slip relative to the bottom collar of the hose. As a result, the graph using the datum measurements was omitted because the slippage at both 150 lbf and 250 lbf loads invalidated the datum test data. In addition, the correct alignment of these Kellems was carefully verified for future loadings. The data collected using the tape measure method can be seen in Fig. 9. The maximum loaded length of 32 inches occurred at a load of 250 lbf while the maximum unloaded length of 31.875 inches occurred at no load. However, the 32 inch maximum loaded length is within the margin of error of the tape measure, as seen by the close proximity of the error bars in Fig. 9.

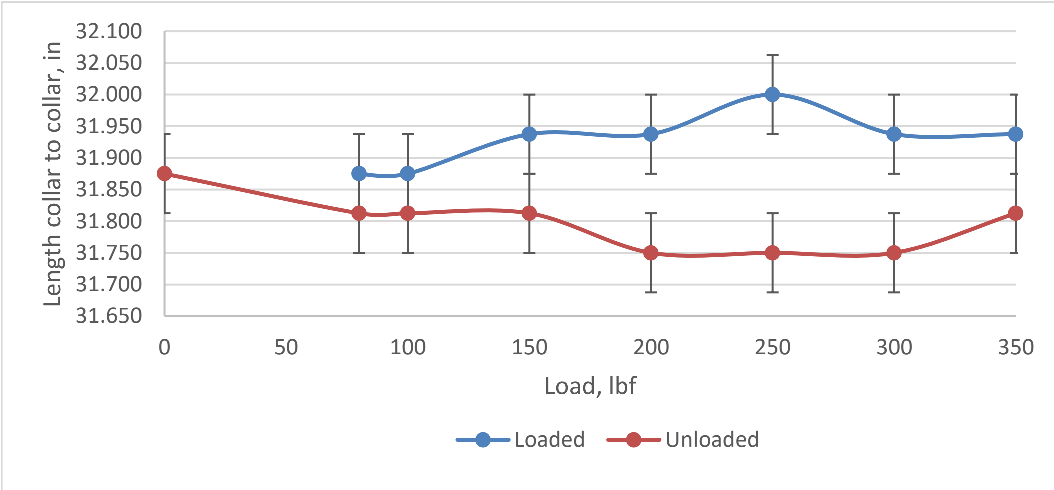

Figure 9. Length of first flex-hose during run 2 using tape measure

The length of the hose unloaded at the beginning of the test fluctuated within a 1/8th of an inch throughout the test. Although the beginning length of the hose is the maximum recorded unloaded length, this variation is negligible due to the accuracy of the tape measure. On the other hand, the flex-hose experienced measureable changes in the loaded length measurements throughout the test. For example, the loaded length of the hose increased from 31.875 inches to 31.9375 inches. This slight elongation of the hose could possibly be explained by the shock loading experienced by the hose at 150 when lbf load. A shock loading at this weight caused the hose to stretch slightly, and this is supported by the consistency of the hose's length for the remaining portion of the test. In omitting the measurement of the hose at 250 lbf due to shock loading, the loaded length of the flex-hose remained at 31.9375 inches consistently within a 1/8th of an inch. Similarly, the unloaded length of the flex-hose remained consistently 31.8125 inches within a 1/16th of an inch margin of error as seen in Fig. 9. As a result of the negligible variation in the unloaded length, the flex-hose can be said to have not experienced inelastic yielding from both the static and shock loadings applied.

C. Testing of Second Hose

Two hoses have been successfully tested at the time of this report and one more test will be conducted once the third and final hose is received. The second EDU flex-hose was loaded according to the previously mentioned revised procedure and no relative slippage occurred at any stage of the test. Throughout the test, data was collected for both methods of measuring length, including unloaded and loaded lengths. This data is summarized in Table 3 below. Also, the recording of the unloaded and loaded lengths of the hose using the tape measure can be seen in Fig. 10. Using this measurement method, a maximum loaded length of 32 inches occurred both at 250 lbf and 350 lbf. As a result, the maximum elongation of the flex-hose was 0.0625 inches. Therefore, the recorded maximum loaded length of 32 inches is within the margin of error as seen in the 1/16th of an inch error bars in Fig. 10. In addition, the unloaded length of the hose did not change significantly during the test.

Table 3. Length measurements of second EDU flex-hose under different loads

Weight, lbf	Unloaded Length Collar to Collar, in	Loaded Length Collar to Collar, in	Unloaded Length Tape Datum, in	Loaded Length Tape Datum, in
0	31.750	31.750	0.094	0.094
80	31.750	31.875	0.125	0.188
100	31.750	31.938	0.156	0.219
150	31.750	31.938	0.156	0.219
200	31.813	31.938	0.156	0.250
250	31.813	32.000	0.125	0.281
300	31.813	31.938	0.125	0.313
350	31.813	32.000	0.188	0.313

Moreover, the initial unloaded length of the tape datum was 0.094 inches, as seen in Table 3. This non-zero initial amount is the result of shifts in the tape datum measurement system during installation of the hose into the fixture.

The string is not easily adjusted once installed, therefore, the non-zero initial value is used as a baseline comparison. In addition, the fluctuation of the data in Table 3 is within the 1/16th of an inch margin of error for the tape measure method, as seen in the error bars in Fig. 10.

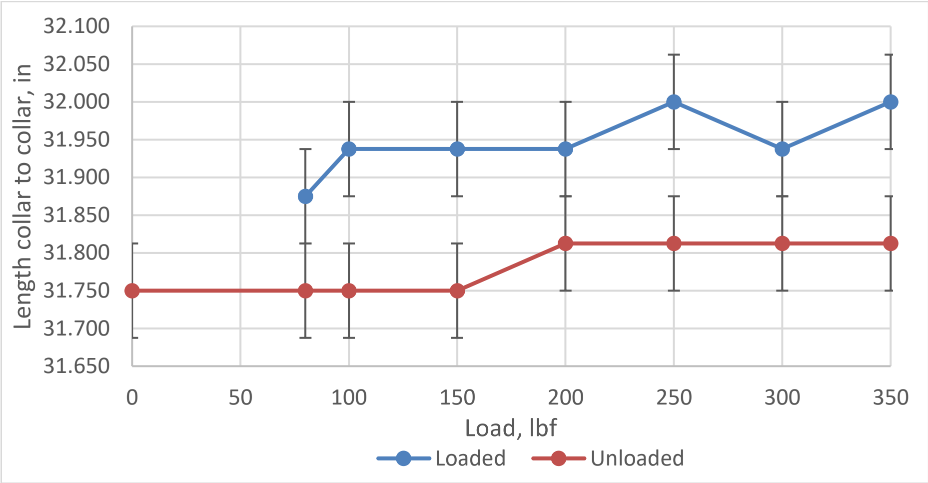

Figure 10. Length of second flex-hose using tape measure

Furthermore, the tape datum measuring method showed a maximum unloaded elongation of 0.094 inches after a loading weight of 350 lbf. In comparison, a maximum loaded elongation of 0.219 inches was achieved with a load of 300 lbf. A graph of the tape datum measuring method data can be seen in Fig. 11. The margin of error in the tape datum measuring method can be seen in the 1/32nd of an inch error bars in Fig. 11.

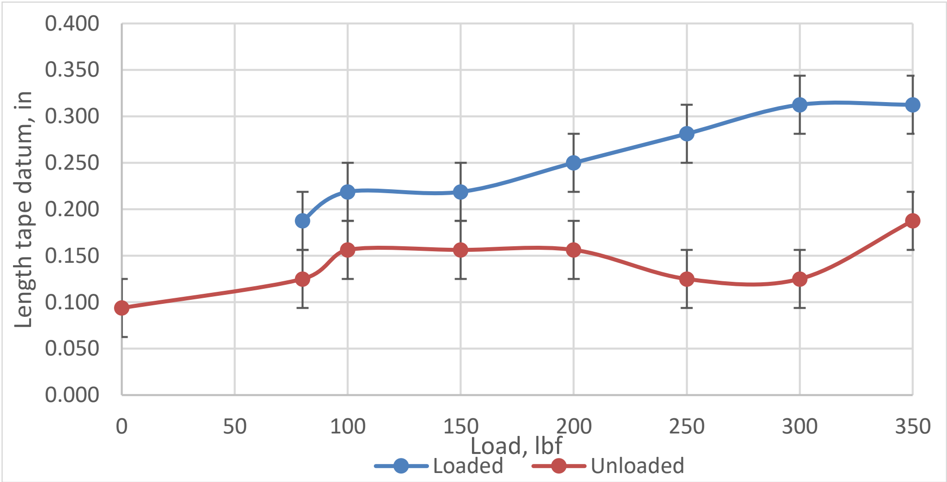

Figure 11. Length of flex-hose using tape datum method

Dissimilar to the previous testing of the first EDU flex-hose, the second flex-hose remained secured and therefore only experienced static loading. Furthermore, accurate testing data was obtained for both measurement methods throughout the experiment. Using the tape measure data, the unloaded length of the flex-hose increased a 1/16th of an inch from the initial length of 31.750 inches to 31.8125 inches. Thus, with a permanent elongation of less than a 1/8th of an inch, the flex-hose did not undergo any inelastic yielding.

Nevertheless, the elongation of the hose during loading was not negligible. An elongation of 3/16th of an inch was recorded consistently for several loadings, indicating that the elastic stretching during loading is considerable. However, this elastic stretching does not compromise the performance of the hose and can be recovered once the unit is unloaded.

In addition to the tape measure data, the datum measurement data provided a similar trend. Summarized in Table 4, the loaded elongation of the hose was calculated by taking the difference between the datum measurements before and after the load is applied. In addition, the total elongation was calculated by subtracting the initial datum value of 0.094 inches from each unloaded length of the tape datum in Table 3. The maximum loaded elongation of 0.1875 inches occurred at a load of 300 lbf before recovering to a total elongation of 0.03125 inches.

Table 4. Stretching of the second flex-hose measured with tape datum

Weight, lbf	80	100	150	200	250	300	350
Loaded Elongation, in	0.0625	0.0625	0.0625	0.09375	0.15625	0.1875	0.1250
Total Elongation, in	0.03125	0.0625	0.0625	0.0625	0.03125	0.03125	0.09375

Moreover, Table 4 describes the amount the flex-hose stretched relative to its unloaded length at each load through the loaded elongation measurements. In comparison, the total elongation data in Table 4 describes the total stretching of the flex-hose dependent on the initial gauge length of the hose.

However, there exists a greater variability of the data collection using the datum method due to the orientation of the string. As a result, sources of error are present in positioning the string parallel to the flex-hose and maintaining constant contact with the flex-hose. The result is less accuracy in recording the true elongation of the flex-hose. Thus the maximum total elongation of 0.094 inches at a load of 350 lbf is not indicative of inelastic yielding. In support of this claim, the increase in the load from 200 lbf to 250 lbf lead to a lower displacement of the flex-hose, proving there is considerable variation in this measurement method.

V. Conclusion

In conclusion, the two EDU flex-hoses tested in tension in the EDO test facility did not experience inelastic yielding within margins of safety. There is therefore no evidence to suggest that tension loads of 200 lbf or less would compromise the ability of these flex-hoses to meet the minimum mission standards. At the time of this report, the recommendation is to proceed with the testing of the full-scale flex-hoses at the flex-hose manufacturer.

Appendix

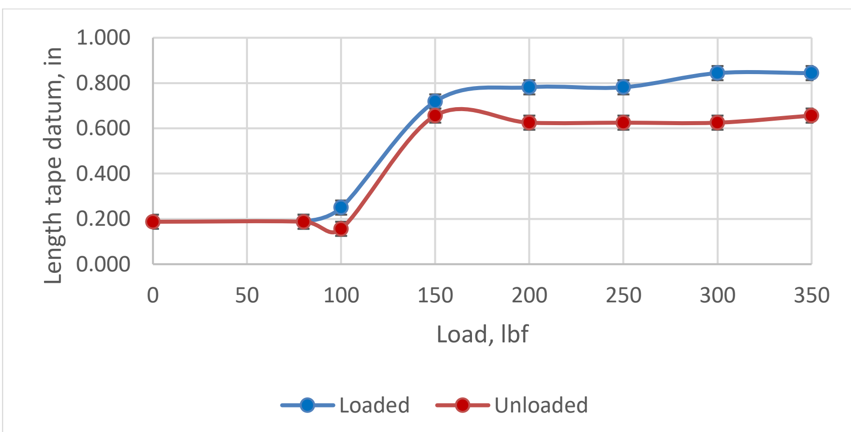

Figure 12. Length of first flex-hose during run 2 using datum measurements. Kellem slippage occurred and invalidated this datum measurement data.

Acknowledgments

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