



Wire and Cable Cold Bending Test

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Abstract

One of the factors in assessing the applicability of wire or cable on the lunar surface is its flexibility under extreme cold conditions. Existing wire specifications did not address their mechanical behavior under cold, cryogenic temperature, conditions. Therefore tests were performed to provide this information. To assess this characteristic 35 different insulated wire and cable pieces were cold soaked in liquid nitrogen. The segments were then subjected to bending and the force was recorded. Any failure of the insulation or jacketing was also documented for each sample tested. The bending force tests were performed at room temperature to provide a comparison to the change in force needed to bend the samples due to the low temperature conditions. The results from the bending tests were plotted and showed how various types of insulated wire and cable responded to bending under cold conditions. These results were then used to estimate the torque needed to unroll the wire under these low temperature conditions.

Introduction

Transferring power is a key aspect to a lunar power system design. The ability to expand the power grid, incorporate additional power generating sources and grow the system as the power demands increase is dependent on the ability to move power from the sources to the loads effectively and efficiently.

Utilizing power cables to provide this power transfer capability is a very efficient method with significant heritage in terrestrial power grids. However, the lunar environment provides a number of challenges to cable design and operation that are unique when compared to earth based transmission systems. Surviving the harsh lunar environment for extended periods of time (on the order of 10 years or so) is a design challenge for most materials and systems, including power distribution cables.

The design of the cables will require easy deployment; be safe to the personal that will be working and living near them; and survive for an extended period of time within the lunar environment.

The power transmission cable consisting of the conductor wire and its associated insulation will need to be capable of operating in and surviving within this environment. The effects of the lunar environment will dictate the installation, placement and design of the cable. Therefore a key aspect of the cable design will be to understand how these environmental conditions affect different materials and combinations of materials that could potentially be utilized in the power cable construction. Some of the environmental effects that would need to be evaluated include the following;

- Effect of vacuum on the cable insulating materials, out-gassing and change in material characteristics.
- Effect of cold on the cable (insulation around the wire), brittleness and flexibility
- Effect of UV radiation on the cable (insulation around the wire), material characteristics changes, brittleness.
- Thermal expansion/contraction effects on the cable, cracking and breaking due to the difference in the coefficient of thermal expansion between the insulators and wire.
- Radiation resistance of the cable, change in material properties, brittleness
- Effect of lunar dust on cable connectors

- The potential and effect of self-heating of the cable due to internal resistance in the wire under daytime conditions on the lunar surface or beneath the highly insulating regolith.

The effect of cold on the cable materials is the first series of testing that was performed. The method of performing this testing as well as the results obtained is detailed in the following sections. The evaluation of the other environmental conditions is tentatively planned as a follow-on effort.

Cold Wire Bending Test Description

The initial series of this testing was performed under the present scope of the program. This consisted of a cold wire-bending test. This testing evaluated the effect of the low temperature (approximately 75 K) had on the mechanical and physical properties of the wire samples.

Wire samples were placed into a liquid nitrogen bath and allowed to equilibrate at the liquid nitrogen temperature. The samples were then removed from the liquid nitrogen, inspected for any obvious structural failures and then placed on a bending press. A bending test was then performed to assess both the flexibility of the wire and the force required to bend it while at or near the liquid nitrogen temperature. The test setup and equipment is shown in Figures 1 and 2.

The test procedure for performing the cold wire-bending test is outlined below.

1. A wire sample approximately 20 cm in length is initially tested at room temperature. The wire is placed across the supports at the base of the bending press. The bending press is activated, pushing the center of the wire down approximately 3 cm. The bending force is subsequently automatically recorded by the press and transferred to the computer.
2. The tested wire is inspected for any cracks or other structural defects and then straightened, if necessary. If any structural problems are documented.
3. The room temperature testing is performed on all of the wires to be tested.
4. Once the room temperature testing is completed, the wires are placed in a stainless steel holding basket.
5. The lid is removed from the liquid nitrogen dewar, and the basket containing the wires is immersed in the liquid nitrogen. The lid is replaced and it is left for the wire temperature to equilibrate for approximately 10 minutes.
6. The dewar lid is removed and the basket holding the wires is removed, one of the wires is removed utilizing stainless steel tongs. The basket and the remaining wires are placed back into the dewar and the dewar lid is replaced.
7. The cold wire is then placed on the support bracket of the bending test machine.
8. The bending press is then activated and the bending force is recorded.
9. Once the test is complete, the wire is then removed from the press and placed in a container on the test table and allowed to come back to room temperature.
10. Once at room temperature, the wire is inspected for any structural failure. Any failures are then documented.
11. The test is repeated for all of the wire samples in the dewar.

The bending test provided data on the force or load required to bend the wire over the range of motion of the test actuator. As the actuator pressed into the cable, the bending radius of the cable changes and the required force to bend it will therefore change. This arrangement is illustrated in Figure 3.

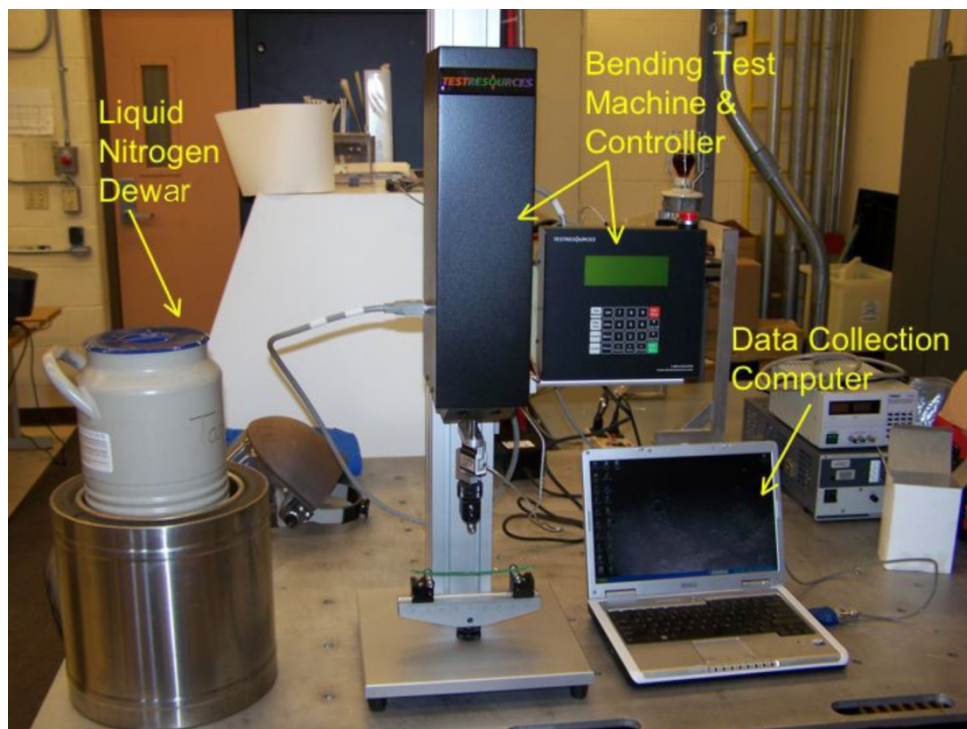


Figure 1.—Cold wire bending test equipment.

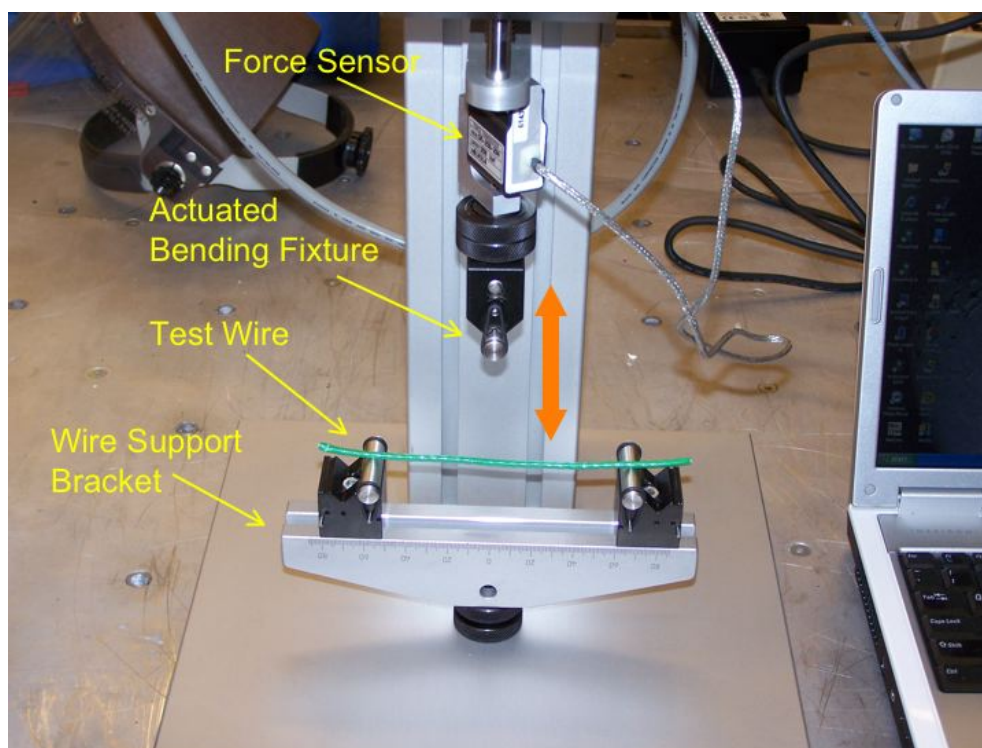


Figure 2.—Bending fixture and wire placement.

The radius of curvature the wire can be determined as a function of the position of the actuator pin with reference to the support pins (y). The radius of curvature for a point along a curve, $y(x)$, is given by Equation (1).

$$R(x) = \frac{(1 + y'(x)^2)^{3/2}}{y''(x)} \quad (1)$$

It was assumed that the wire shape would be that of a parabola, given by Equation (2). From this equation the focus of the parabola (a) can be determined for various positions of the actuator (y). For this testing the distance between the center of the actuator pin and the front of the support pin (x) was set at 60 mm.

$$y = \frac{x^2}{4a} \quad (2)$$

Substituting Equation (2) into Equation (1) yields an expression for the radius of curvature, or bending radius, along the wire, given by Equation (3).

$$R(x) = 2a + \frac{x^3}{4a^2} \quad (3)$$

The maximum radius of curvature will occur at the $x=0$ location, given by Equation (4).

$$R = 2a \quad (4)$$

This radius and the bending force applied can be used to determine the torque required to unroll the cable from a reel at low temperatures.

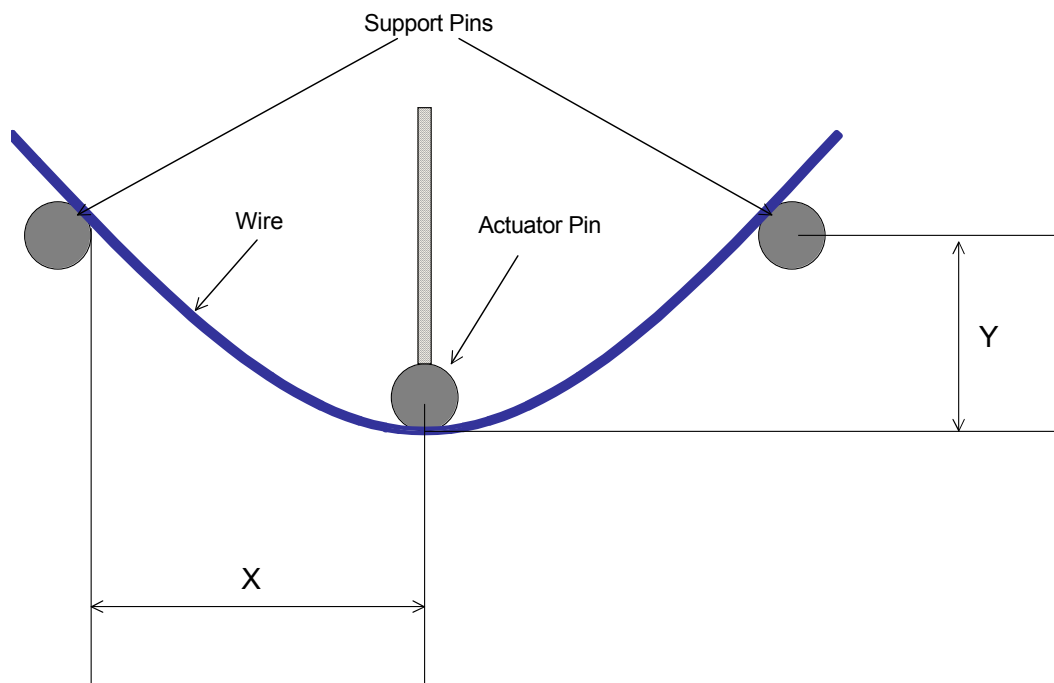


Figure 3.—Diagram of 3-Point Wire Bending

The torque (T) due to the bending force of the wire is simply the force (F) needed to bend the wire multiplied by the radius (r) of the wire reel. This is given by Equation (5).

$$T = Fr \quad (5)$$

The radius of curvature is also known as the bending radius, the smaller the bending radius the greater the bend in the wire.

Wire Samples

A number of different wire samples were collected and tested at both room temperature and at liquid nitrogen temperatures. The wire samples differed in gauge and insulation material. These wire samples represented a range of wire types commonly used in space applications. Their testing at the extreme cold temperature of liquid nitrogen will begin to build a database of what off-the-shelf types of wires and eventually cabling may be applicable to the lunar environment. Details on the wire samples that were tested are given in Table 1.

TABLE 1.—TEST WIRE AND CABLE INFORMATION AND CHARACTERISTICS

Description	Gauge	Conductors/insulation	Insulation thickness (mm)	Wire thickness (mm)	Voltage (V)	Designation and notes
1. Stranded copper (Green)	12	Single-PVC	0.711	1.88	600	DU-437-229, E194201, VW-1 Rated
2. Stranded Copper (Red with Black Lettering)	10	Single-PVC	0.9398	2.3114	600	DU-437128, THWN or THHN or MTW
3. Stranded Copper (White)	12	Single-NA	0.7874	1.8542	600	DU-437-229, E194201, VW-1 Rated, THWN or THHN or MTW
4. Stranded Copper (Pink)	10	Single-Silicon Rubber	0.9652	2.3876	NA	Very flexible even at liquid nitrogen temperatures
5. Stranded Copper (Blue)	10	Single-NA	0.7493	2.6162	600	T80 Nylon or TWN75 FTI Type MTW or THNN or THWN , Cracked during bending at liquid nitrogen temperature
6. Stranded Copper (White)	10	Single-NA	0.7747	2.6162	600	E53446, Essex Type, THWN or THHN or MTW, VW-1
7. Stranded Copper (Gray)	10	Single-PVC w Nylon Cover	0.9271	2.3368	600	Ceno Wire Vinylon-1, THWN or THHN or MTW, VW-1
8. Stranded Copper (White)	12	Single- NA	0.8382	1.9431	600	E148891J, THWN or THHN or MTW
9. Stranded Copper (Light Blue)	12	Single- NA	0.6985	2.0066	600	DU-437-084
10. Stranded Copper (Red)	18	Single- Silicon Rubber	1.3716	1.0668	NA	EPDM
11. Stranded Copper (White)	20	Single-Teflon	0.4445	0.7747	NA	
12. Stranded Copper (Blue)	18	Single- Teflon	0.4445	1.1049	NA	
13. Stranded Copper (Orange)	12	Single-Kapton	0.2159	2.0574	NA	
14. Stranded Copper (Yellow)	12	Single-Kapton	0.2286	1.9558	NA	
15. Copper Stranded (White)	18	Single-Silicon Rubber	2.5781	0.6477	40,000	Style 3239 150 C VW-1 E61355, Very flexible even at liquid nitrogen temperature.
16. Copper Stranded (Red Black Lettering)	14	Single-PVC w Nylon Cover	0.5842	1.6256	600	THHN or THWn or MTWRD T90
17. Copper Stranded (White)	16	Single-Silicon Rubber	1.4097	1.2192	20,000	150°C FT2-LF E211048 AWM Style 3239, Very flexible even at liquid nitrogen temperature.
18. Copper Stranded (Black)	16	Single-PVC w Nylon Cover	0.6477	1.1938	600	Essex Class-K Type TFFN or MTW E10048, 15 mil insulation, 4 mil Nylon
19. Solid Core Wire Type-T Thermocouple	26	2 Conductor with outer jacket-NA	0.2413	0.4064	NA	

TABLE 1.—TEST WIRE AND CABLE INFORMATION AND CHARACTERISTICS

Description	Gauge	Conductors/insulation	Insulation thickness (mm)	Wire thickness (mm)	Voltage (V)	Designation and notes
20. Copper Stranded (Green)	6	Single-PVC w Nylon Cover	1.3716	3.5814	600	THHN Encore Wire VW-1 MTW or THHN or THWN-2, Shattered during bending at liquid nitrogen temperature.
21. Copper Stranded (Red)	6	Single-PVC	1.524	3.6322	600	E69996 W Type THHN or THWN or MTW or AWM VW-1, Shattered during bending at liquid nitrogen temperature.
22. Copper Stranded (Black)	14	Single-NA	1.651	1.6764	NA	Pink Rubber like inner insulation with black rubberized jacket, Cracked during bending at liquid nitrogen temperature.
23. Copper Stranded (Gray)	22	6 conductor insulated wire with additional un-insulated ground wire. Metal foil inner wrap on the wire and outer plastic jacket.-PVC	0.3048	0.4953	NA	#962/0036 FT. IR22SAL-50 Isotec Inc. CL3R or MPT or CMR (UL) C(UL) CMG FT-9 11/01/99-2LL Outer jacket cracked during bending at liquid nitrogen temperature.
24. Aluminum Stranded (Black)	20	2 Conductor Wire with additional un-insulated ground wire.-NA	0.254	0.6477	NA	
25. Copper Stranded (Gray)	22	2 Conductor Wire with additional un-insulated ground wire.-NA	0.3556	0.4953	NA	West Penn Wire / Cut #291 1 PR Shielded (UL) Type CMR C(UL) 75 C B0055 999388 Feet
26. Solid Core (Bronze)	10	Single-Varnish	0.0889	2.2987	NA	Electric motor winding wire, Small cracks in the varnish during bending at liquid nitrogen temperature.
27. Copper Stranded (Black)	18	Single-Peek	0.4953	0.9906	NA	Peek
28. Copper Solid Core with Stranded Copper outer wrap (Light Blue)	24	2 Conductor Coax-NA	0.66 outer 0.66 inner	0.4699	NA	
29. Aluminum Stranded core with braded aluminum outer wrap (Black)	24	2 conductor Coax-NA	0.546 outer 0.959 inner	0.4699	NA	Precision Video
30. Copper Stranded core with braded aluminum outer wrap (Black)	24	2 conductor Coax-NA	0.572 outer 1.016 inner	0.457	NA	Brilliance Video
31. Aluminum solid core with braded aluminum outer wrap (Brown)	18	2 conductor Coax-NA	0.686 outer 1.01 inner	0.953	NA	Themrax
32. Copper Solid Core with Stranded Copper outer wrap (Black)	20	2 Conductor Coax-NA	0.851 outer 1.07 inner	0.813	NA	RG 58/U, RG058RT
33. Aluminum Stranded core with braded aluminum outer wrap (Light Brown)	28	2 conductor Coax-NA	0.279 outer 0.635 inner	0.292	NA	
34. Stranded Aluminum (White)	14	Single-NA	0.406 outer 3.175 inner	1.689	NA	Braided cloth over plastic outer jacket with a hard plastic inner insulation
35. Stranded Copper (White)	14	Single-Teflon	0.445	1.880	NA	Super-TEK

Testing Results

The force applied by the actuator as it moved and bent the wire was recorded for each of the wire samples tested. The force versus time curves were plotted for the various gauge or types of wires. The bending radius was also plotted on each graph. By looking at both the bending radius plot and the force curve for a given wire type, the force needed to unreel or reel the wire can be determined for a given reel radius. The bending force curves for the various wires are plotted in Figures 4 through 8. The wire numbers listed on the graphs correspond to those given in column 1 of Table 1. In general the bending force curves all follow the same pattern as should be expected. As the bending radius decreases the required bending force increases. The change in the bending radius is the greatest at the beginning of the bending process and then tapers off. The change in bending force follows the same pattern. It initially increases rapidly as the bending radius is decreasing and then levels off as the change in the bending radius also levels off.

The bending curves for the 10-gauge wire samples that were tested are given in Figure 4. From this figure it can be seen that there was a significant increase in the required bending force between the room temperature and liquid nitrogen temperature tests. There was approximately a fivefold increase in the bending force between the wire at room temperature and at liquid nitrogen temperature. The insulation on wires number 2 and 5 failed during the liquid nitrogen temperature testing. This can be seen by the steep drop-off in the load at around 15 s for wire 5 and just before 18 s for wire 2.

The 12 gauge wire bending results are given in Figures 5 and 6. These results are similar in pattern to the 10 gauge results shown in Figure 4. Overall the bending force is less than that for the 10 gauge wires, as would be expected. The average maximum force for the cold temperature bending for the 12 gauge wires was approximately 15 N where as for the 10-gauge wire it was approximately 30 N. The slight change in wire diameter between the 10 and 12 gauge wires produced a significant change in cold wire bending force. The exception to this was for the Kapton insulated wires, shown in Figure 6. For the Kapton insulated wires the bending force applied was much less than the force applied with other types of insulation. This lower bending force can be attributed to the significantly thinner insulation thickness of the Kapton insulation compared to that of the other 12 gauge wires.

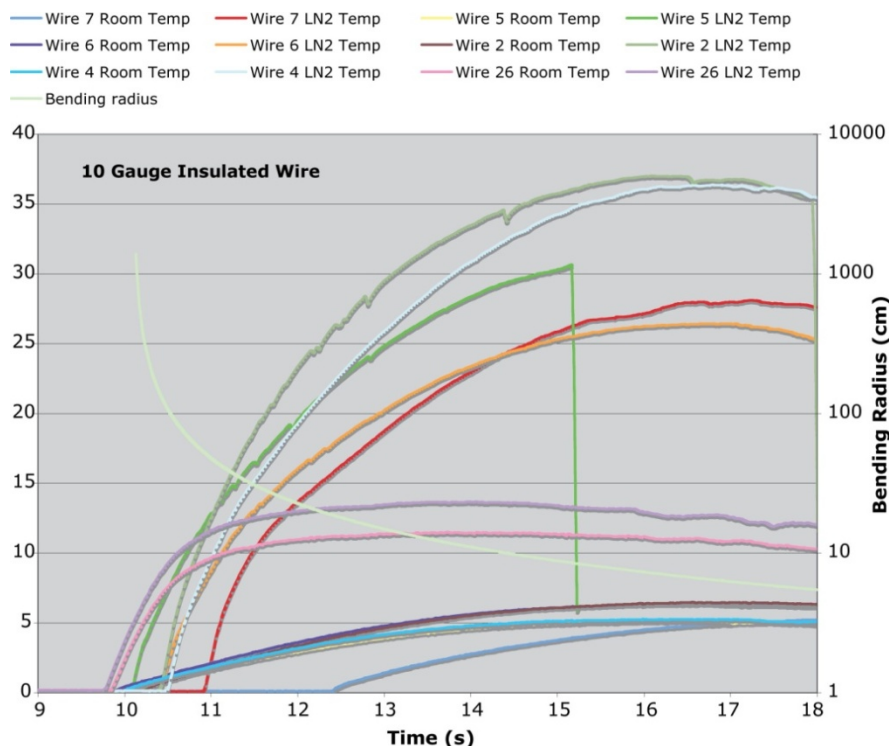


Figure 4.—Bending force curves for 10 gauge wire samples.

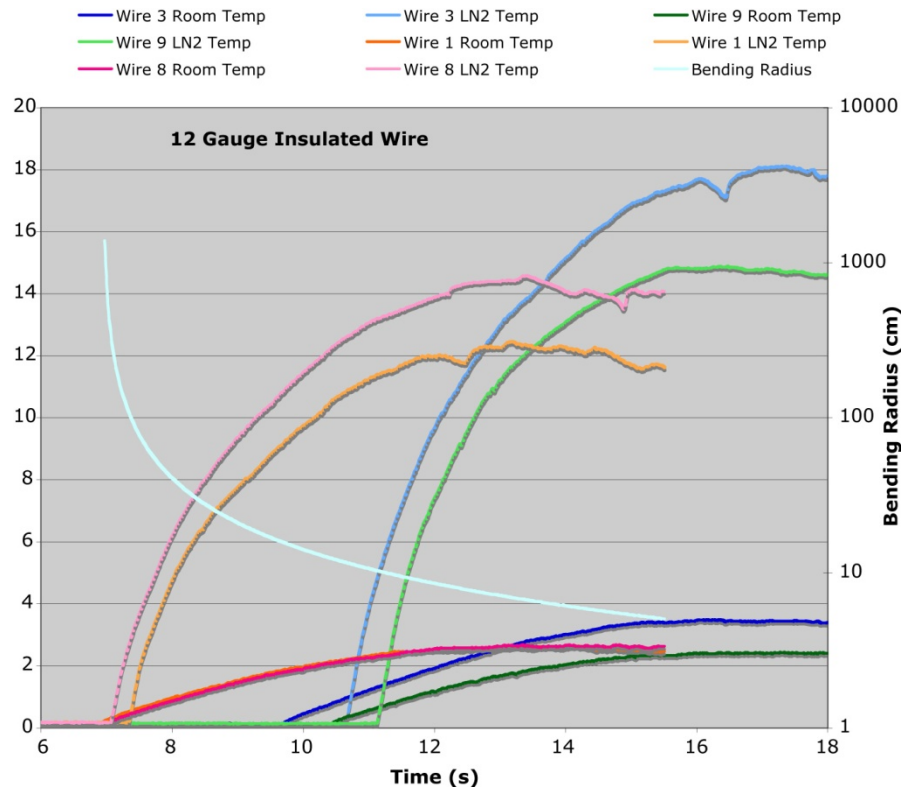


Figure 5.—Bending force curves for 12 gauge wire samples.

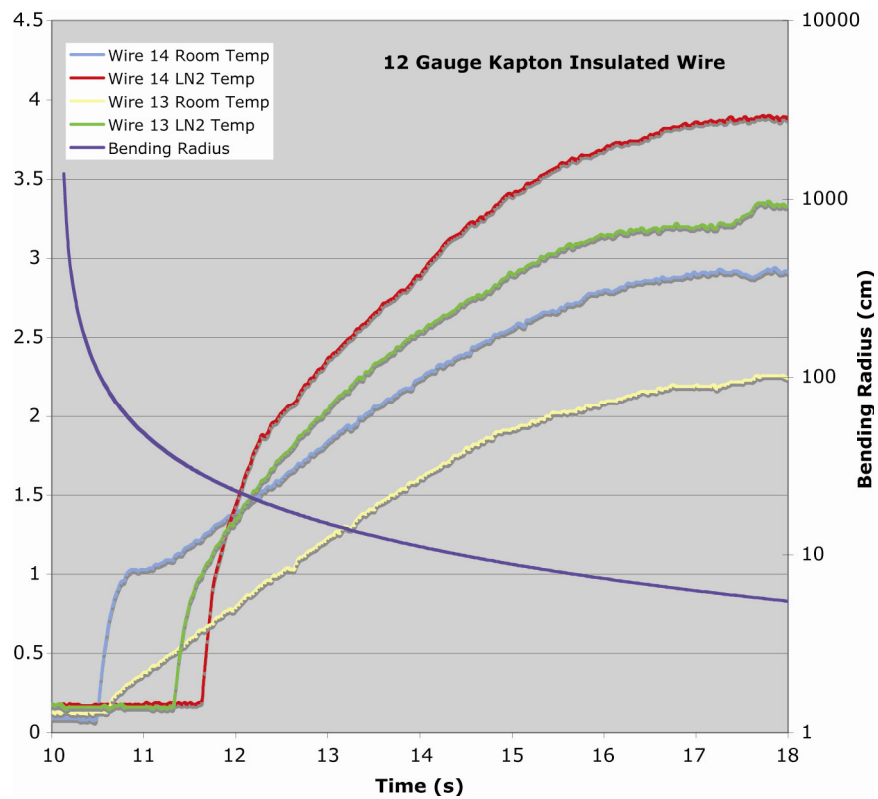


Figure 6.—Bending force curves for Kapton insulated 12 gauge wire.

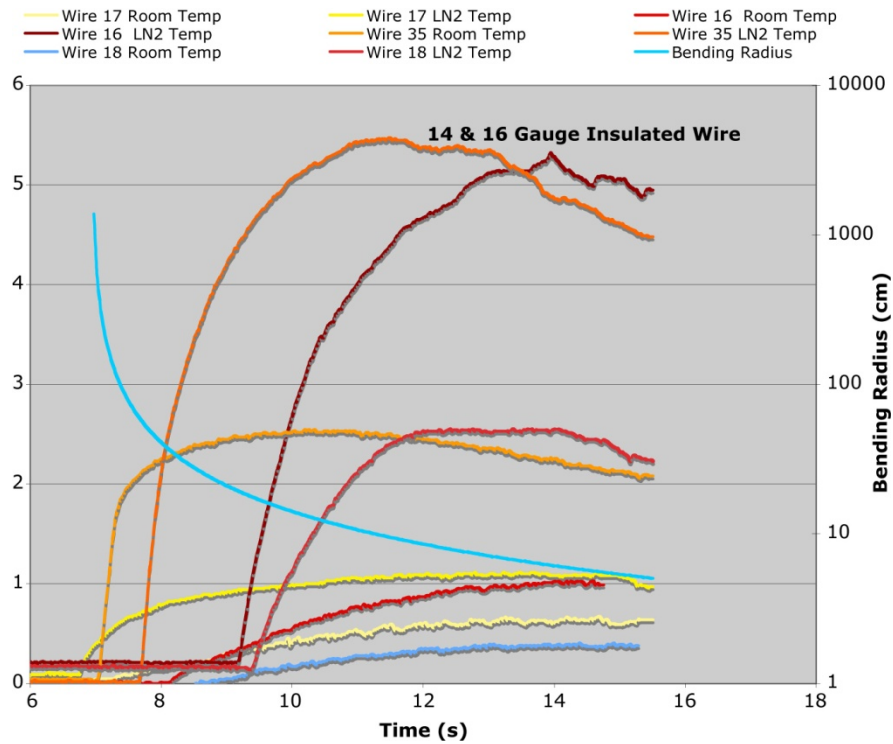


Figure 7.—Bending Force Curves for 14 and 16 Gauge Wire

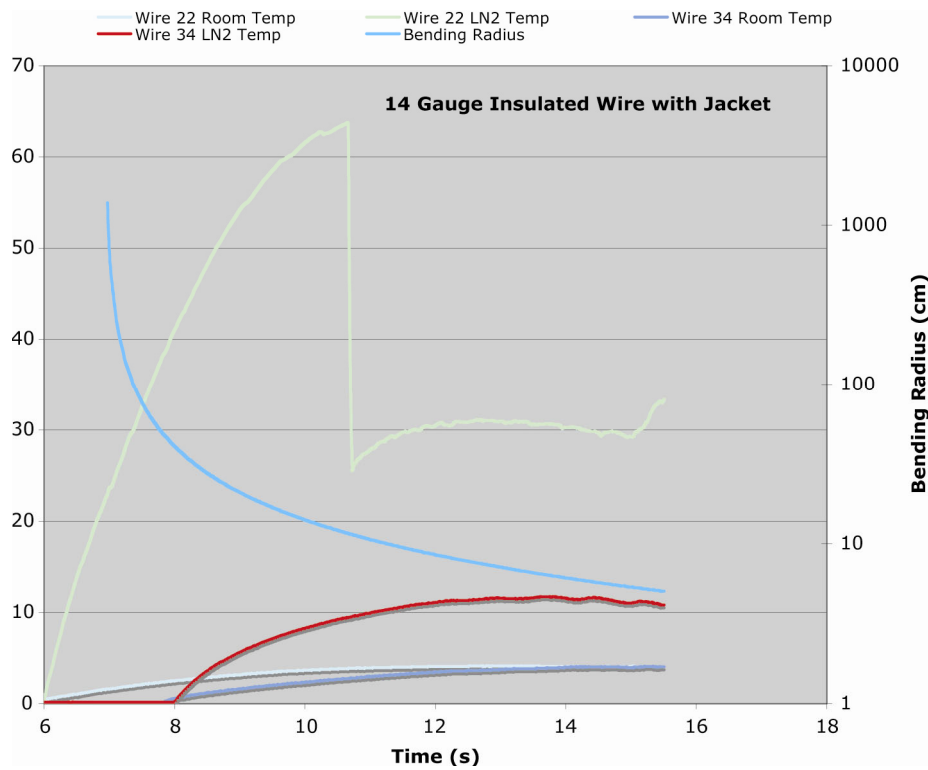


Figure 8.—Bending Force Curves for Insulated 14 Gauge Wire with Jacket

The bending force for the 14 and 16 gauge wires is shown in Figures 7 and 8. Figure 7 shows bending force curves for insulated 14 and 16 gauge wire. These curves follow the typical pattern shown in the previous graphs. From this graph it can be seen that the bending force for the 14-gauge wire was about twice that of the 16 gauge wires, both at room temperature and liquid nitrogen temperatures. The forces for the 14 gauge wires shown in Figure 8 are significantly greater than those given in Figure 7. The insulation on wires 22 and 34 was significantly different than the others 14 gauge wires that were tested, in both construction and thickness. It consisted of an outer jacket wrapping an inner layer of insulation. Also it should be noted that the insulation on wire 22 failed during the testing as can be seen by the sharp drop-off in the bending load at approximately 11 s.

The smallest gauge wires that were tested were 6-gauge. The bending force results for these wires are given in Figure 9. It should be noted that the insulation on both of these wires failed during the liquid nitrogen temperature bending. This failure is illustrated on the graph by the sharp drop-off in the load profile, which occurred at approximately 9 s for wire 20 and 10.5 s for wire 21. A picture of wire 21 before and after the liquid temperature bending is shown in Figure 10. In this picture the fracture of the insulation is clearly visible. The failure of both the 6 gauge wires indicates that as the wire thickness increases the susceptibility of the wires to failure under extreme cold conditions increases. Both the 6 gauge wires tested had PVC insulation with a nylon covering. Other, higher gauge wires also utilized this same type of insulation. The majority of these thinner wires with the same type of insulation did not fail during the cold bending test.

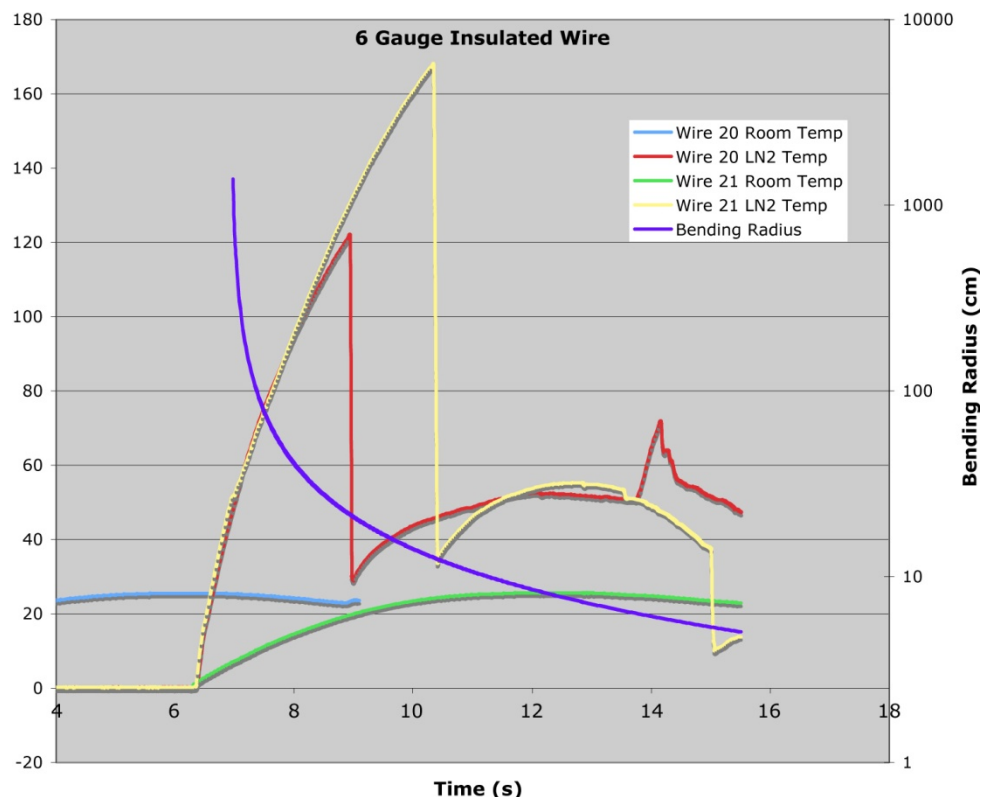


Figure 9.—Bending force curves for 6 gauge insulated wire.

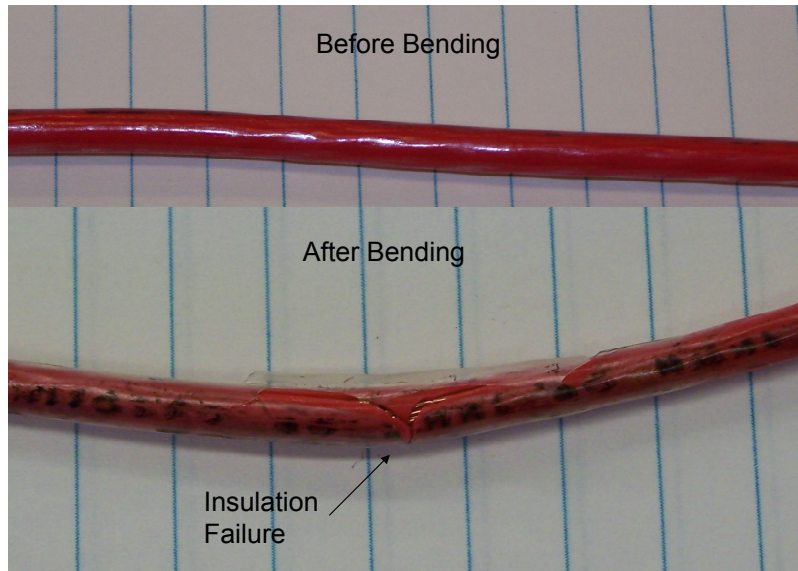


Figure 10.—Before and after bending of 6 gauge wire at liquid nitrogen temperature.

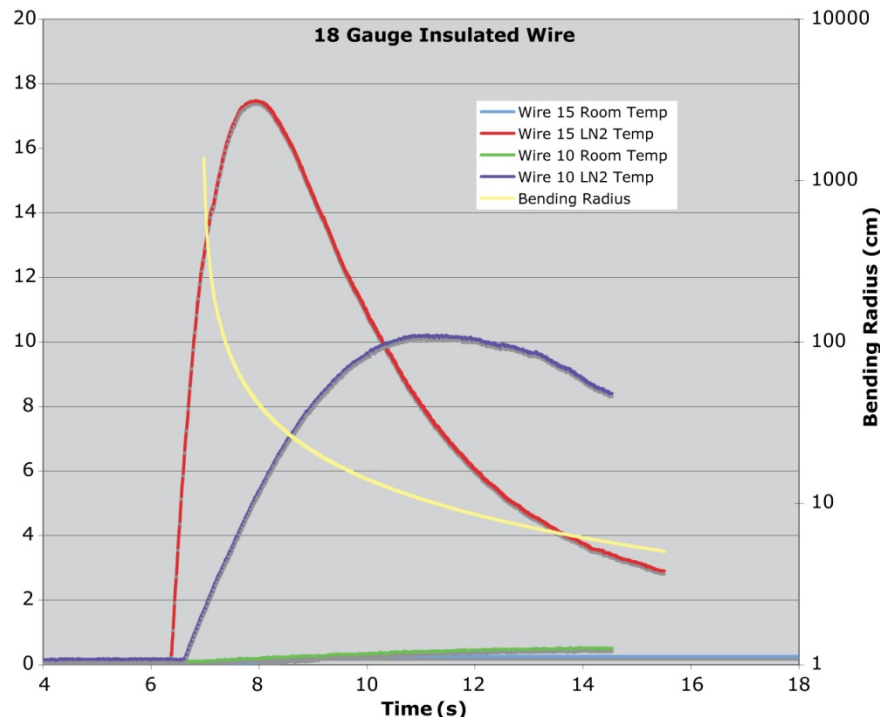


Figure 11.—Bending force curves for 18 gauge insulated wire.

The next figures are for the highest gauge single wires tested. Figure 11 shows the bending force curves for two 18-gauge wires. The bending force at liquid nitrogen temperatures for these wires is significantly higher than those for the 16 or 14 gauge wires. This is because although the wire thickness of these 18 gauge wires is smaller the insulation thickness is greater. Wires 10 and 15 both have silicon rubber insulation that is utilized for high voltage applications and is therefore significantly thicker than the other types of insulation utilized in the 14 or 16 gauge wire tests.

The next series of results are for multiple wire cables. These consisted of a number (2 or more) of insulated wires bundled together with or without an outer jacket. These results are shown in Figure 13.

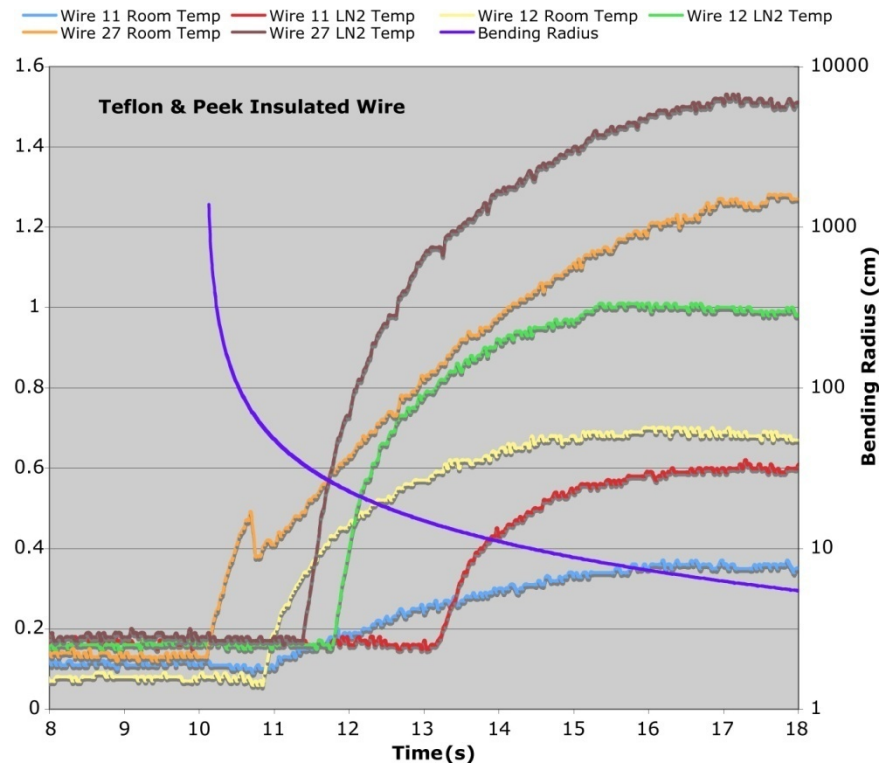


Figure 12.—Bending force curves for 18 and 20 gauge Teflon and Peek insulated wires.

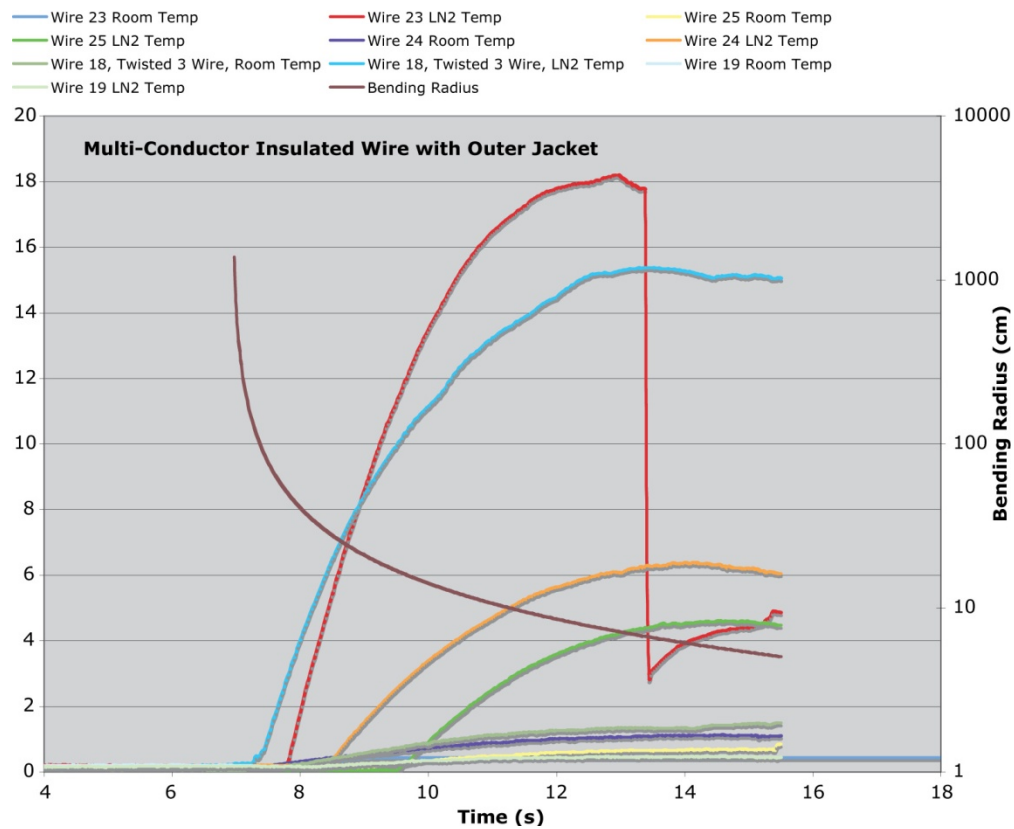


Figure 13.—Bending Force for Multi-Wire Cable

As an additional direct comparison the bending curves for wire 3 (16 gauge PVC insulation with a nylon over wrap) were plotted both as a single wire and as the three wire twisted cable. This plot is shown in Figure 14. This figure shows that the bending force of the twisted three-wire cable at room temperature is approximately three times as much as for the single cable. However, at liquid nitrogen temperatures the bending force for the three-wire cable approximately six times as great as that for the single wire. This indicates that at low temperatures the bending forces of a multi-wire cable do not scale linearly with bending forces of the wires that constitute the cable. Therefore minimizing the number of wires in a cable or using multiple cables with lower wire counts each could help minimize the force needed to deploy the cable.

The final series of multi-wire cable testing was performed on coaxial (Coax) cable. The coaxial cable that was tested all had a similar configuration. The cables have a central conductor, which is either a solid core or stranded wire surrounded by insulation. On the outside of this inner insulation is a second conductor consisted of stranded wire. This outer ring of stranded wire is covered with an insulating jacket. A diagram of the internal layout of a standard Coax cable is shown in Figure 15.

The bending force results for the Coax cables are shown in Figures 16 and 17. Figure 16 shows the bending force curves for various types of Coax cables and Figure 17 shows a comparison in bending force between a single Coax cable and a dual Coax cable. The dual cable consisted of two Coax cables of similar type with the outer jackets joined together. From Figure 17 it can be seen that the bending force required for two joined coax cables at liquid nitrogen temperatures is much greater than twice the force required for a single cable. This is a similar result as seen with the multiple wire bending curves, shown in Figure 14. This again indicates that to minimize the required deployment force, the number of wires on a given cable should be minimized.

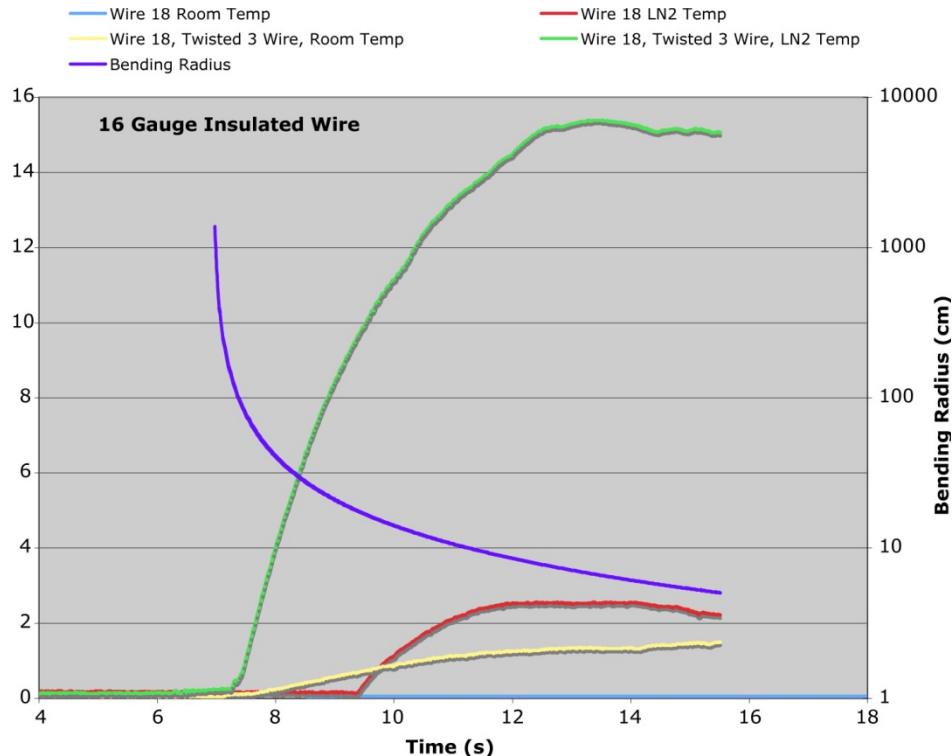


Figure 14.—Single and twisted three-wire bending force comparison.

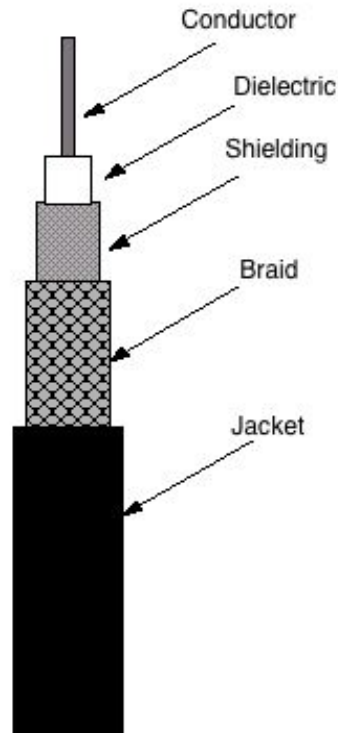


Figure 15.—Coax cable component construction diagram.

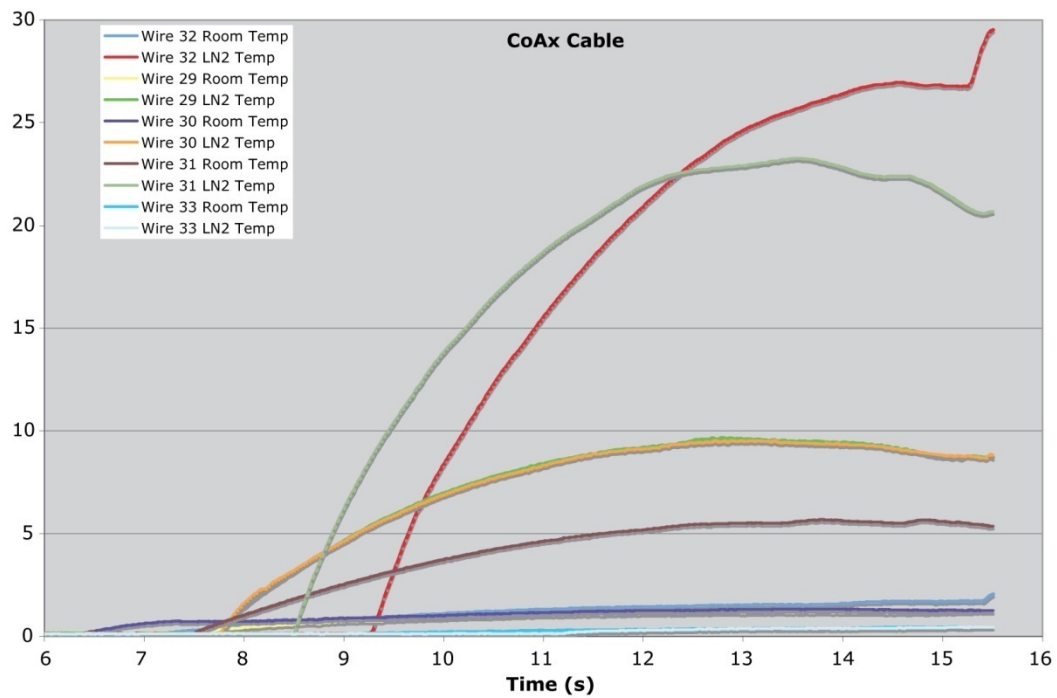


Figure 16.—Coax cable bending force curves.

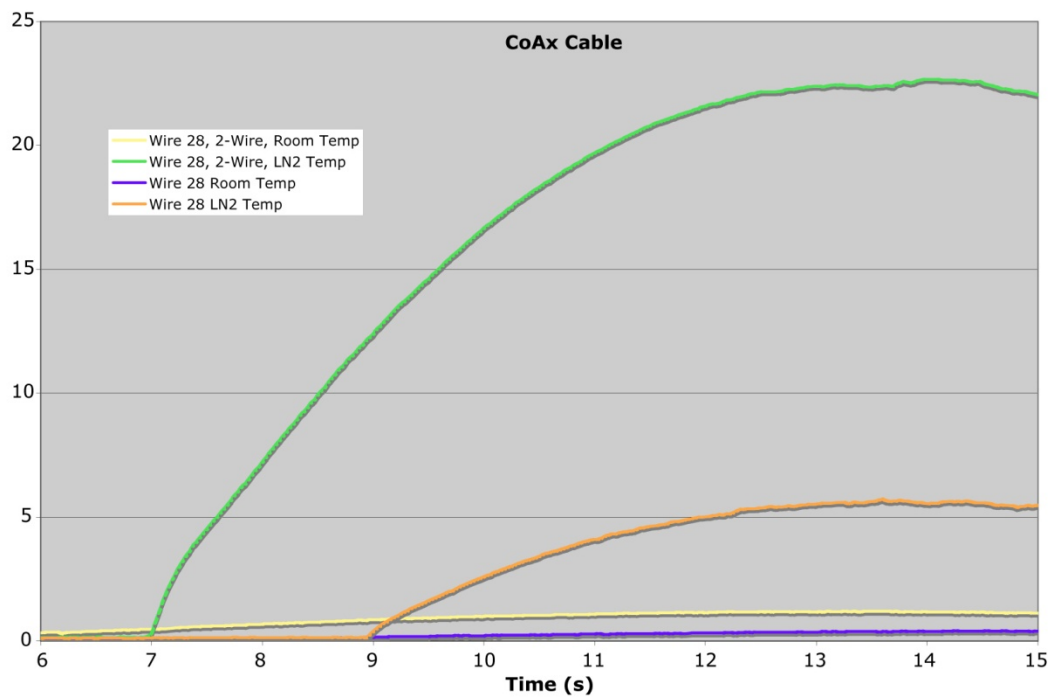


Figure 17.—Comparison of single and dual coax bending force curve.

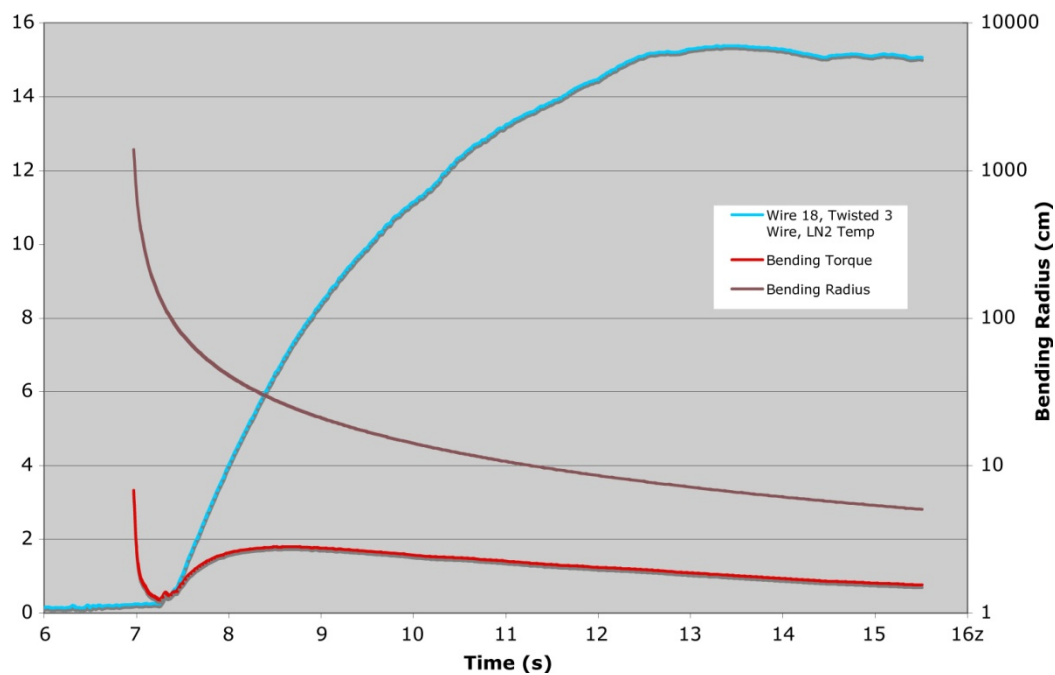


Figure 18.—Rotational torques from wire bending.

The bending forces shown in the above figures can be applied to the reeling in or deployment of cable. For a spinning reel, the force due to the bending of the cable as it comes off or is put onto the reel will add to the torque necessary to turn the reel. As would be expected and illustrated in the previous figures, this bending force is greater at cold temperatures.

An example of the additional torque produced on a cable reel by the bending of the wire or cable is shown in Figure 18. This figure is for the twisted three-wire cable at liquid nitrogen temperature. The figure shows the force required to bend the wire, the subsequent bending radius associated with that force and the corresponding torque that would be generated on the axis of a reel that would be paying out or in the cable.

From this figure it can be seen that over the majority of the range the torque decreases with decreasing bending radius even though the bending force is increasing. This is due to the rate of decrease in the bending radius being greater than the rate of increase in bending force. This trend should be representative of all the wires and cables tested.

Conclusion and Summary

The majority of the wires performed well at the liquid nitrogen temperatures. The mechanical failure of the insulation was not common. For the failures that did occur, it was with the lower gauge wires and those with thicker insulation. The wire size tended to be a critical factor as to whether a particular type of insulation would fail. For example, both 6 gauge wires with PVC insulation (wires 20 and 21) failed during testing. However, a number of higher gauge wires utilizing the same type of insulation did not fail (1, 2 and 16, gauges 12, 10 and 14 respectively).

Insulation thickness also played a critical role in the required bending force for the wires at cold temperatures. In general the testing showed that the thicker the insulation the greater the increase in bending force between room temperature and liquid nitrogen temperature. For example wires 10 and 15 had some of the largest insulation thicknesses of the wires tested. Both these wires showed significant increase in bending force (20 to 40 times greater) when cold compared to bending at room temperature. This contrasts with wire 26 which had a very thin insulation layer. The bending force increase on this wire when cold was only on the order of 15%.

The results for the multiple wire cables were similar to those of the individual wires tested. Insulation thickness and outer jacket type and thickness played a significant role in the resultant bending force. One notable comparison is between a standard 2-conductor wire (cable number 24) and a 2-conductor coaxial cable (cable number 32) with the same wire gauge. The standard two conductor cable, number 24, had an approximate six times increase in bending force at liquid nitrogen temperatures versus room temperature, whereas the co-ax cable (number 32) had a 27 times increase in force. It should be noted that the room temperature force needed to bend each of these cables was approximately the same.

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14. ABSTRACT One of the factors in assessing the applicability of wire or cable on the lunar surface is its flexibility under extreme cold conditions. Existing wire specifications did not address their mechanical behavior under cold, cryogenic temperature conditions. Therefore tests were performed to provide this information. To assess this characteristic 35 different insulated wire and cable pieces were cold soaked in liquid nitrogen. The segments were then subjected to bending and the force was recorded. Any failure of the insulation or jacketing was also documented for each sample tested. The bending force tests were performed at room temperature to provide a comparison to the change in force needed to bend the samples due to the low temperature conditions. The results from the bending tests were plotted and showed how various types of insulated wire and cable responded to bending under cold conditions. These results were then used to estimate the torque needed to unroll the wire under these low temperature conditions.					
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