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Comparative Performance Data for Extra-High Strength Copper Alloy Conductors

RATIONALE

This SAE Aerospace Information Report (AIR) documents comparative performance data for an extra-high strength copper alloy relative to high strength and ultrahigh strength copper alloys, silver and nickel coated. Testing was performed using the test protocol of AS6324, which includes testing of insulated and connectorized wires that have been subjected to conditioning via thermal aging, thermal shock, and vibration.

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1. SCOPE

This AIR is limited to the testing of an extra-high strength copper alloy and benchmark conductors utilizing the test protocol of AS6324. All samples are 19 strand unilay conductors per AS29606 at 24 or 26 AWG, either nickel or silver coated. At 24 AWG, extra-high strength copper alloy is compared to high strength copper alloy conductors. At 26 AWG, extra-high strength copper alloy is compared to high strength copper alloy and ultrahigh strength copper alloy conductors.

1.1 Purpose

The purpose of the work documented in this AIR is to provide data to designers and users indicating the performance and potential applicability of wires produced using conductors of extra-high strength copper alloys. The testing and results presented in this report provide a robust comparison to more familiar alloys to aid in contextualizing the results. The protocol of AS6324 was used as a standard regiment of tests that has been established to demonstrate capability of conductor alloys.

2. APPLICABLE DOCUMENTS

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (U.S. and Canada only) or +1 724-776-4970 (outside U.S. and Canada), www.sae.org.

AS4373	Test Methods for Insulated Electric Wire
AS5768	Tool, Stripper, Electrical Insulation, General Specification For
AS6324	Verification of New Conductor Alloys for AS29606 Conductors Qualification
AS22520	Crimping Tools, Wire Termination, General Specification For
AS22759	Wire, Electrical, Fluoropolymer-Insulated, Copper or Copper Alloy
AS22759/33	Wire, Electrical, Fluoropolymer-Insulated, Cross-Linked Modified ETFE, Lightweight, Silver-Coated, High-Strength Copper Alloy, 200 °C, 600 Volt, ROHS
AS22759/55	Wire, Electrical, Fluoropolymer-Insulated, Cross Linked Modified ETFE, Lightweight, Silver Coated, Extra High Strength Copper Alloy, 200 °C, 600 Volt, ROHS
AS22759/82	Wire, Electrical, Polytetrafluoroethylene/Polyimide Insulated, Light Weight, Nickel Coated, High Strength or Ultra High Strength Copper Alloy, 260 °C, 600 Volt, ROHS
AS22759/94	Wire, Electrical, Polytetrafluoroethylene/Polyimide Insulated, Lightweight, Nickel Coated, Extra High Strength Copper Alloy, 260 °C, 600 Volt, ROHS
AS29606	Wire, Electrical, Stranded, Uninsulated Copper, Copper Alloy, or Aluminum, or Thermocouple Extension, General Specification for
AS39029	Contacts, Electrical Connector, General Specification For
AS50881	Wiring Aerospace Vehicle

2.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9500, www.astm.org.

ASTM B263/B263M	Standard Test Method for Determination of Cross-Sectional Area of Stranded Conductors
ASTM B470	Standard Specification for Bonded Copper Conductors for Use in Hookup Wire for Electronic Equipment
ASTM B624	Standard Specification for High-Strength, High-Conductivity Copper-Alloy Wire for Electronic Application

2.3 ECIA Publications

Available from Electronic Components Industry Association, 310 Maxwell Road, Suite 200, Alpharetta, GA 30009, Tel: 678-393-9990, www.ecianow.org.

EIA-364-08 Crimp Tensile Strength Procedure for Electrical Connectors

2.4 Global Electronics Association Publications

Available from Global Electronics Association, 3000 Lakeside Drive, 105 N, Bannockburn, IL 60015, Tel: 847-615-7100, www.electronics.org.

J-STD-002 Solderability Tests for Component Leads, Terminations, Lugs, Terminals and Wires

2.5 NEMA Publications

Available from National Electrical Manufacturers Association, 1812 N. Moore Street, Suite 2200, Arlington, VA 22209, Tel: 703-841-3200, www.makeitelectric.org.

NEMA WC-67 Uninsulated Conductors - Used in Electrical and Electronic Applications

2.6 U.S. Government Publications

Copies of these documents are available online at <https://quicksearch.dla.mil>.

MIL-STD-202 Electronic and Electrical Component Parts

MIL-STD-2223 Test Methods for Insulated Wire

3. BACKGROUND

Historically, when the ultrahigh strength copper alloy class was introduced, the alloy underwent a series of system level wire qualification tests before being approved for use. That testing was the basis of testing performed on the first cadmium-free high strength copper alloy and provided the foundation and rationale for the introduction of AS6324 as the requirement for qualifying new conductor alloys. That testing is important for designers to better understand the implications of using a new alloy and for users to have confidence in the performance of the alloy. To date, similar test results have not been publicly available for an extra-high strength alloy conductor. Therefore, that robust test protocol, now formally AS6324, is being applied to an already approved extra-high strength copper alloy, which includes comparison to the most common currently used, well-established copper alloy classes at 24 and 26 AWG.

The results indicate potential opportunities relative to increased flex life and weight savings available to designers for applications that could take advantage of the unique combination of strength and conductivity provided by extra-high strength copper alloy conductors.

4. SPECIMENS

4.1 Conductors

The test program evaluated specimens using 24 and 26 AWG conductors in both silver- and nickel-coated configurations. All samples were 19 strand unilay stranded constructions, which for 24 AWG is 19 strands of 36 AWG single ends and for 26 AWG is 19 strands of 38 AWG single ends. At 24 AWG, the comparison was between a commonly used high strength copper alloy and an extra-high strength copper alloy. At 26 AWG, the extra-high strength copper alloy was compared to both a high strength copper alloy and an ultrahigh strength copper alloy.

[Table 1](#) displays the conductor configurations used in the evaluation. All the conductor specimens were produced by Fisk Alloy Inc. of Hawthorne, NJ, using their high strength copper alloy, Percon 24, extra-high strength copper alloy, Percon 28, and ultrahigh strength alloy, Percon HS95. The requirements in accordance with AS29606 allow for a wide diameter range for a given gauge size. This can influence the primary characteristics of direct current resistance and break load, which may present a challenge to making valid comparisons. To minimize the contributions of conductor size and focus comparisons on the alloy alone, conductors with the same construction were manufactured to a similar size and weight per unit length.

Annealed soft copper conductors were included in the test program for use only in flex life testing to establish a baseline for flex life results. These specimens are 24 gauge silver-plated copper, 24 gauge nickel-plated copper, and 26 gauge silver-plated copper.

4.1.1 Sample Identification

The following convention is used for sample conductor identification. See REF in tables.

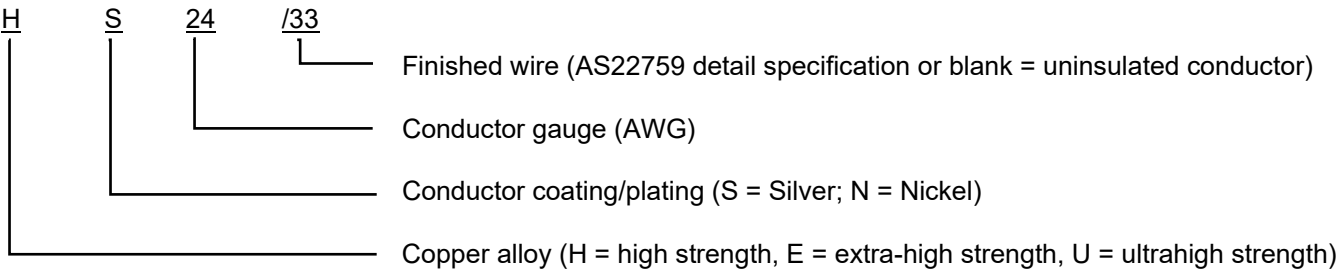


Table 1 - Conductor configurations

REF	MATERIAL	COATING	GAUGE	STRANDS	DIAMETER (inch)		MAX RESISTANCE (ohms/1000 feet)	AS29606B TABLE / TYPE
					MIN	MAX		
HS24	High Strength Copper Alloy	Silver	24	19x36	0.0225	0.0244	28.4	4C / SCA
ES24	Extra-High Strength Copper Alloy	Silver	24	19x36	0.0231	0.0244	28.4	4G / SCS
HN24	High Strength Copper Alloy	Nickel	24	19x36	0.0225	0.0254	30.1	4C / NCA
EN24	Extra-High Strength Copper Alloy	Nickel	24	19x36	0.0231	0.0254	30.1	4G / NCS
HS26	High Strength Copper Alloy	Silver	26	19x38	0.0175	0.0194	44.8	4C / SCA
ES26	Extra-High Strength Copper Alloy	Silver	26	19x38	0.0184	0.0194	44.8	4G / SCS
UN26	Ultrahigh Strength Copper Alloy	Nickel	26	19x38	0.0175	0.0204	58.4	4E / NCU
EN26	Extra-High Strength Copper Alloy	Nickel	26	19x38	0.0184	0.0204	49.4	4G / NCS
CS24	Copper	Silver	24	19x36	0.0225	0.0244	24.3	4A / SCC
CN24	Copper	Nickel	24	19x36	0.0225	0.0244	25.9	4A / NCC
CS26	Copper	Silver	26	19x38	0.0175	0.0194	38.4	4A / SCC

4.2 Insulated Wires

The insulated wire samples were prepared as specified in AS6324. The silver-plated conductors were insulated with extruded cross-linked modified ethylene-tetrafluoroethylene (XL-ETFE) by Judd Wire Inc. of Turners Falls, MA. The nickel-plated conductors were insulated with tape wrapped polytetrafluoroethylene/polyimide (PI/PTFE) by Carlisle Interconnect Technologies (now Amphenol CIT) of St. Augustine, FL. The corresponding AS22759 slant sheets are provided in [Table 2](#) and are included in the sample reference.

Table 2 - Insulated wire configurations

REF	Type / Code	GAUGE	INSULATION	DIAMETER (inch)		MAX WEIGHT (lb/1000 ft)	MAX RESISTANCE (ohms)	AS22759 SHEET
				MIN	MAX			
HS24/33	Silver-Coated High Strength (SCA)	24	XL-ETFE	0.035	0.039	2.00	28.4	/33
HN24/82	Nickel-Coated High Strength (NCA)	24	PI/PTFE	0.034	0.038	2.00	30.1	/82
ES24/55	Silver-Coated Extra-High Strength (SCS)	24	XL-ETFE	0.035	0.039	2.00	28.4	/55
EN24/94	Nickel-Coated Extra-High Strength (NCS)	24	PI/PTFE	0.034	0.038	2.19	30.1	/94
HS26/33	Silver-Coated High Strength (SCA)	26	XL-ETFE	0.030	0.034	1.40	44.8	/33
ES26/55	Silver-Coated Extra-High Strength (SCS)	26	XL-ETFE	0.030	0.034	1.40	44.8	/55
EN26/94	Nickel-Coated Extra-High Strength (NCS)	26	PI/PTFE	0.030	0.034	1.57	49.4	/94
UN26/82	Nickel-Coated Ultrahigh Strength (NCU)	26	PI/PTFE	0.030	0.034	1.45	58.4	/82

4.3 Termination Contacts

The termination contacts used for testing are listed in [Table 3](#). The same barrel diameter is used for 24 AWG and 26 AWG constructions and therefore resulted in a less than optimal crimp performance for many of the 26 AWG conductors. However, this was selected to show a realistic scenario of potential performance. Upon review of the results, it should be considered that the crimp performance may be improved for 26 AWG products by using a smaller, more appropriately sized barrel contact.

Table 3 - List of contact materials used for testing

Pin	Socket
D38999/26WH35PN Pin Plug	D38999/24WH35SN Receptacle
M39029/58-360 Pins	M39029/56-348 Sockets
M22520/2-09 Positioner	M22520/2-07 Positioner
M22520/2-01 Crimp tool	M22520/2-01 Crimp tool

5. TEST PROCEDURE

A review and discussion of select test requirements to provide insight into what was tested, and why, as well as highlighting critical aspects will follow. For a review of the extra-high strength copper alloy test results and analysis, proceed directly to Section 6.

The testing is divided into two primary groups, the first being characterization and testing of the uninsulated conductors. The second group, which encompasses the bulk of the work, is tests performed on insulated and environmentally conditioned samples which in some cases required connectorization.

5.1 Uninsulated Conductor Test Requirements

Uninsulated conductor requirements are listed in [Table 4](#). In general, these requirements are the standard lot verification for conductor requirements (diameter, resistance, break load, coating thickness, etc.) with the addition of the Temperature Coefficient of Resistance (TCR), Thermal Softening Behavior (TSB), and flex life. These three additions, in particular the TSB and Flex Life, are important because they demonstrate the metallurgical performance and integrity of the conductor during insulation and in use.

Table 4 - Uninsulated conductor test requirements

Test Name	AS6324 Section
Diameter	5.1.1.1
Conductor Cross-Sectional Area	5.1.1.2
Weight	5.1.1.3
Temperature Coefficient of Resistance	5.1.2
Conductor Resistance	5.1.3
Conductor Elongation and Tensile Breaking Strength	5.1.4
Coating Thickness	5.1.5
Coating Adhesion (Nickel coated only)	5.1.6
Conductor Strand Blocking	5.1.7
Thermal Softening Behavior	5.1.8
Flex Life	5.1.9
Solderability (Silver coated only)	5.1.10

5.1.1 Thermal Softening Behavior

Conductors typically are insulated at elevated temperatures, which may lead to softening and a reduction in the strength of the material. This could lead to, for example, premature failure, a degradation in performance if stretched, or inadequate crimp strength. In addition, depending on the insulation, coating/plating, and/or connector, there is an expectation for a minimum operating temperature without softening or other deleterious effects. While the elevated temperature performance can be validated by system level testing (which is done as part of AS6324 validation), an important additional test is the TSB to clearly establish the softening performance of the alloy. TSB is an excellent tool for comparing the expected high-temperature performance of various alloys. The TSB performance is dependent on the chemical composition and processing of the conductor and is therefore an indicator of the quality and consistency of the chemistry and processing.

5.1.2 Flex Life

Generally, the flex life increases/decreases with the strength of the conductor. The higher the strength, the higher the flex life. However, for complex alloy systems and production processes, testing the flex life provides an additional layer of verification that there is nothing within the conductor that would contribute to premature flex failure. It is known that the insulation can strongly influence the flex life, but to test the robustness of the conductor itself, it is important to test the uninsulated conductor.

There are many variables that can influence the flex life, whether relating to the conductor being tested (i.e., coating/plating type, surface roughness, presence of inclusions, etc.) or the test fixture (i.e., minimizing rotation and vibration, perfectly locating the mandrel at the axis of rotation, controlling the acceleration of the test head, etc.), making flex life testing inherently difficult to control. Therefore, it is important that the same test equipment and testing procedure is utilized for the reference and trial material.

To account for inherent variability between test fixtures and to prevent confusion and misinterpretation of the number of cycles to failure that may be related more to the fixture than the conductor, AS6324 requires that the flex life be reported as a value relative to the flex life of copper. This does provide a means to normalize the data and focus on the relative performance; however, it introduces an extra layer of testing complexity by necessitating copper samples be also tested as part of the test protocol. While this is useful, the same objective of presenting only relative values can be achieved by reporting the results relative to the reference alloy.

5.1.3 Temperature Coefficient of Resistance (TCR)

The TCR is important for a new alloy since it indicates electrical performance as a function of temperature and is also required to perform temperature adjustments for lot qualification testing. TCR testing is not an indicator of product performance but is a material characteristic that needs to be known for using the conductor.

5.2 Insulated and Conditioned Wire Test Requirements

While the performance of the conductor alone can indicate performance after insulation and connectorization, it is important to simulate conditions that could potentially lead to failures for new alloys which have not yet demonstrated application performance.

The purpose of the conditioning is to determine if the conductor will be influenced by environmental conditions in use, i.e., exposure to elevated temperatures, thermal cycling, and/or vibration. It is important to be sure there are no attributes of the conductor that could cause a degradation in performance under these environmental conditions.

The requirements for the tests to be applied for various conditions for insulated and insulated conditioned wire testing is specified in AS6324. There are three sets of conditioned wire: thermal aging, thermal shock, and vibration conditioning. Some of the wires are terminated and some are tested without termination. In some cases, the contacts are to be removed and re-crimped for retesting. For temperature conditioning, the required temperature depends on whether the conductor coating is silver or nickel, as well as the temperature rating of the contacts. To simplify the above and make it more visual, the test requirements for insulated wire are presented in a test matrix in [Table 5](#).

Table 5 - Insulated wire and insulated conditioned wire test descriptions, including recommended number of samples per test

Test	AS6324 Section	Contacts	Pre-conditioning	Thermal Aging ⁽¹⁾	Thermal Shock ⁽¹⁾	Vibration	Thermal Aging Re-terminated	Thermal Shock Re-terminated	Silver Plated, °C ⁽¹⁾	Nickel Plated, °C ⁽¹⁾
Wire Size	5.2.1	No Contacts	3	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Weight	5.2.2	No Contacts	1	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Solderability (Silver Plate)	5.2.3	No Contacts	5	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Voltage Drop	5.2.5	Contacts	3	3	3	5	3	3	200	200
Termination (Pullout) Strength	5.2.6	Contacts	3	3	3	5	3	3	200	200
Flex Life at Crimp Termination	5.2.8.1	Contacts	3	3	3	5	n/a	n/a	200	200
Center-of-Wire Flex Life	5.2.8.2	No Contacts	16	16	16	n/a	n/a	n/a	200	260
Center-of-Wire Tensile Strength	5.2.7	No Contacts	3	3	3	n/a	n/a	n/a	200	260
Conductor Resistance ⁽²⁾	n/a ⁽²⁾	No Contacts	2	2	2	n/a	n/a	n/a	200	260
Strip Force (Strippability)	5.2.9	No Contacts	3	3	3	n/a	n/a	n/a	200	260

⁽¹⁾ Thermal test temperature is either 200 °C or 260 °C depending on coating and/or contact.

⁽²⁾ Conductor resistance is not currently a requirement in AS6324.

Each of the required insulated wire tests are to be performed prior to conditioning to establish the baseline performance. Conductor resistance is not currently a requirement in AS6324 but is measured as part of Voltage Drop testing (refer to AS6324, Voltage Drop, Resistance A). However, due to the importance of the conductor resistance, it was added to the test protocol for extra-high strength copper alloy comparison.

Vibration conditioning is intended to verify the robustness of the interaction with the conductor and the contact at the crimp, and therefore only those tests including contacts (voltage drop, termination strength, and flex life at crimp termination) are required to be performed on the vibration samples.

5.3 Laboratories Conducting Tests

The primary test facility for this program was Underwriters Laboratory (UL). UL subcontracted the solderability testing to Lectromec of Chantilly, VA. UL subcontracted the vibration conditioning activity to Experior Laboratories of Oxnard, CA.

6. RESULTS AND DISCUSSION

Due to the sheer number of tests, conditions, and samples, the volume of data generated from this validation is extensive, and attempts are made to summarize the data to the extent possible to simplify this AIR. This AIR presents the results to demonstrate the performance of extra-high strength copper alloy as compared to other existing alloys as a reference.

6.1 Uninsulated Conductor

Each of the required tests listed in [Table 4](#) were performed. The results are documented below.

6.1.1 Conductor Cross Section

Method: AS29606 and ASTM B263/B263M

The results for determining the CMA using a single strand cross section are displayed in [Table 6](#). The results of calculating the CMA using sample weight per ASTM B263/B263M are listed in [Table 7](#). The CMA calculation using the strand method produces a slightly smaller CMA than does the calculation using the weight method. All the samples met the diameter requirements for AS29606, and there is no significant differences in the conductors at each respective gauge size.

Table 6 - Circular mil area (strand method)

REF	Material	Gauge	CMA (min)	Diameter (Strand)		CMA (Strand)		CMA (19 Strands)	
				#1	#2	#1	#2	#1	#2
HS24	High Strength	24	434	0.00490	0.00495	24.010	24.503	456.19	465.55
ES24	Extra-High Strength	24	434	0.00485	0.00480	23.523	23.040	446.93	437.76
HS26	High Strength	26	275	0.00385	0.00383	14.823	14.669	281.63	278.71
ES26	Extra-High Strength	26	275	0.00400	0.00395	16.000	15.603	304.00	296.45
HN24	High Strength	24	434	0.00490	0.00490	24.010	24.010	456.19	456.19
EN24	Extra-High Strength	24	434	0.00480	0.00485	23.040	23.523	437.76	446.93
EN26	Extra-High Strength	26	275	0.00400	0.00390	16.000	15.210	304.00	288.99
UN26	Ultrahigh Strength	26	275	0.00400	0.00400	16.000	16.000	304.00	304.00

Table 7 - Circular mil area (weight method)

REF	Material	Gauge	CMA (min)	Length (feet)	Mass Factor (f)	K Factor (k)	Weight (pounds)		CMA (19 Strands)	
							#1	#2	#1	#2
HS24	High Strength	24	434	4.00	0.003066	1.18	0.00569	0.00569	458.17	458.24
ES24	Extra-High Strength	24	434	4.00	0.003066	1.18	0.00577	0.00576	464.76	464.56
HS26	High Strength	26	275	4.00	0.003072	1.34	0.00359	0.00359	288.41	288.31
ES26	Extra-High Strength	26	275	4.00	0.003072	1.34	0.00376	0.00376	301.96	301.66
HN24	High Strength	24	434	4.00	0.003044	1.18	0.00567	0.00568	460.24	461.05
EN24	Extra-High Strength	24	434	4.00	0.003044	1.18	0.00581	0.00580	471.60	470.79
EN26	Extra-High Strength	26	275	4.00	0.003044	1.34	0.00371	0.00370	300.66	299.86
UN26	Ultrahigh Strength	26	275	4.00	0.002991	1.34	0.00375	0.00375	309.59	309.61

6.1.2 Diameter, Electrical Resistance, Weight, Break Load and Elongation

The measured properties of the conductors are provided in [Table 8](#) for silver-plated and [Table 9](#) for nickel-plated conductors. The tables include the requirement specified in AS29606. For silver at 26 AWG, in addition to the high strength sample, an ultrahigh strength sample was tested to show the comparison to extra-high strength copper alloy. High strength, and not ultrahigh strength, was used as the comparative insulation sample since there is no XL-ETFE slant sheet for 26 AWG silver-plated ultrahigh strength copper alloy.

Table 8 - Conductor properties, silver-plated (includes AS29606 requirements)

REF	Alloy	Plate	AWG	Source	Diameter Inch		Resistance Max Ω/mft	Weight Max lb/mft	BL Min lbf	EL Min %
					Min	Max				
HS24	High Strength	Silver	24	Req. Result	0.0225 0.0236	0.0244	28.4 24.6	n/a 1.42	22.4 26.0	6 8.4
ES24	Extra-High Strength	Silver	24	Req. Result	0.0231 0.0237	0.0244	28.4 27.1	n/a 1.44	28.7 33.1	6 9.3
HS26	High Strength	Silver	26	Req. Result	0.0175 0.0187	0.0194	44.8 38.8	n/a 0.897	14.2 16.3	6 8.8
ES26	Extra-High Strength	Silver	26	Req. Result	0.0184 0.0191	0.0194	44.8 41.8	n/a 0.938	18.2 21.7	6 9.4
US26	Ultrahigh Strength	Silver	26	Req. Result	0.0175 0.0190	0.0204	56.4 52.5	n/a 0.926	21.5 25.5	6 9.0

Table 9 - Conductor properties, nickel-plated (includes AS29606 requirements)

REF	Alloy	Plate	AWG	Source	Diameter Inch		Resistance Max Ω/mft	Weight Max lb/mft	BL Min lbf	EL Min %
					Min	Max				
HN24	High Strength	Nickel	24	Req. Result	0.0225 0.0235	0.0254	30.1 27.9	n/a 1.42	22.4 27.5	6 8.3
EN24	Extra-High Strength	Nickel	24	Req. Result	0.0231 0.0238	0.0254	30.1 28.4	n/a 1.45	28.7 33.9	6 8.6
UN26	Ultrahigh Strength	Nickel	26	Req. Result	0.0175 0.0193	0.0204	58.4 52.8	n/a 0.937	21.5 23.9	6 10.0
EN26	Extra-High Strength	Nickel	26	Req. Result	0.0184 0.0189	0.0204	49.4 45.1	n/a 0.926	18.2 21.7	6 8.0

In general, the conductors are relatively lightweight compared to the allowable size range. All obtained measurements are within the required ranges and exceed the minimum requirements for the properties for any of the samples.

As an alternative to comparing the actual values, the percent difference in properties is calculated and presented in Tables 10 and 11 for the measured properties DCR and break strength. This shows more clearly how properties of extra-high strength compares with high strength copper alloy. For a much greater increase in break load, there is modest increase in resistance. This improvement is magnified for nickel-plated products as evidenced by HN24 and EN24, where the strength is increased by 23% with only a marginal 2% increase in resistance.

Compared to ultrahigh strength, extra-high strength copper alloy has a lower strength but with a much lower resistance. The break load of the extra-high strength for both the silver and nickel samples meets the minimum requirement of 21.5 lbf for 26 AWG ultrahigh strength copper alloy. This suggests that extra-high strength may be a good candidate for use as a 26 AWG construction, where it has near the needed strength but with much improved resistance.

Table 10 - Percent difference (%Δ) in properties of extra-high strength for silver-plated uninsulated conductors

				Resistance %Δ	Break Strength %Δ
REF	Alloy	Plate	AWG	Ω/mft	lbf
HS24	High Strength	Silver	24	--	--
ES24	Extra-High Strength	Silver	24	10.3%	27.5%
HS26	High Strength	Silver	26	--	--
ES26	Extra-High Strength	Silver	26	7.9%	33.5%
US26	Ultrahigh Strength	Silver	26	--	--
ES26	Extra-High Strength	Silver	26	-20.3%	-14.7%

Table 11 - Percent difference (%Δ) in properties of extra-high strength for nickel-plated uninsulated conductors

				Resistance %Δ	Break Strength %Δ
REF	Alloy	Plate	AWG	Ω/mft	lbf
HN24	High Strength	Nickel	24	--	--
EN24	Extra-High Strength	Nickel	24	1.7%	23.4%
UN26	Ultrahigh Strength	Nickel	26	--	--
EN26	Extra-High Strength	Nickel	26	-14.5%	-9.2%

6.1.3 Thermal Softening Behavior (TSB)

Method: AS6324, Thermal Softening Behavior

The TSB testing specified in AS6324 in the temperature range of 300 to 500 °C goes beyond what is typically considered an operating temperature or those used during insulation for a conductor wire. The goal is to identify at which point the alloy starts to soften and to what degree. The resulting tensile peak load (aka break load, break strength, or tensile load) after exposure to the test temperature for 1, 2, 4, 8, 15, 30, and 60 minutes is plotted exponentially to show trends. Due to good softening performance of the alloys, to better compare performance the scale of break strength in the below figures is magnified to better analyze the changes that occur.

[Figure 1](#) demonstrates the performance of 24 AWG silver-plated extra-high strength (ES24). For samples at 300 °C and 350 °C, the strength is not impacted by temperature, and even at 400 °C slight softening is observed at times longer than 15 minutes. At 450 °C, even though extra-high strength does show a greater degree of softening, it remains above the starting break load for high strength copper alloy. At 500 °C, extra-high strength softens at a greater rate, but since it starts with a higher break load than high strength copper alloy, the BL at 60 minutes is 24 lbf, which is still higher than high strength copper alloy and is greater than the minimum requirement for 24 AWG high strength alloy of 22.4 lbf.

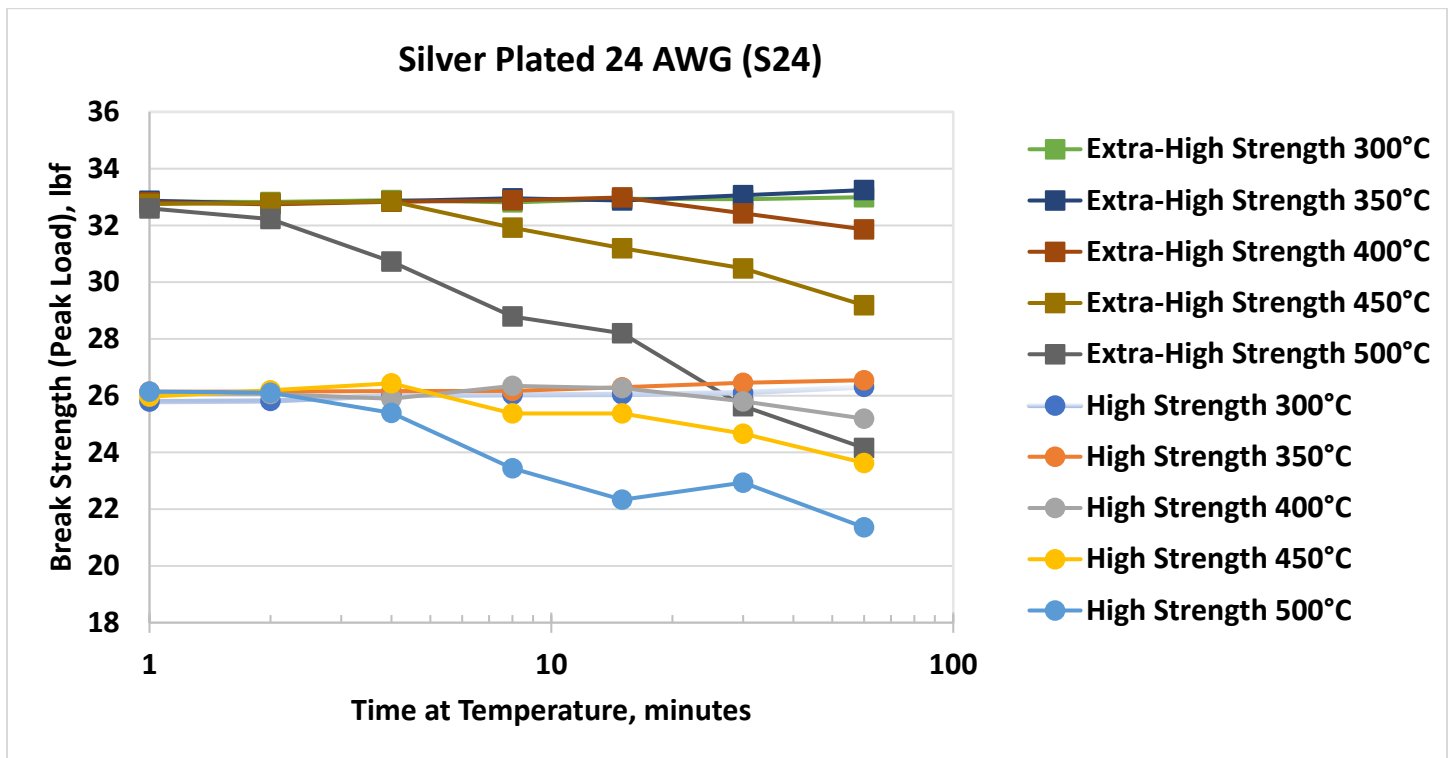


Figure 1 - Thermal softening behavior of silver-plated 24 AWG high strength and extra-high strength

Nickel-plated 26 AWG samples (see [Figure 2](#)) show a similar elevated temperature performance to the silver-plated 24 AWG samples (see [Figure 2](#)), where there is excellent resistance to softening up to 400 °C for both extra-high strength and ultrahigh strength copper alloy. At 500 °C, ultrahigh strength softens more sharply than extra-high strength, resulting in both samples having the same break load at 60 minutes.

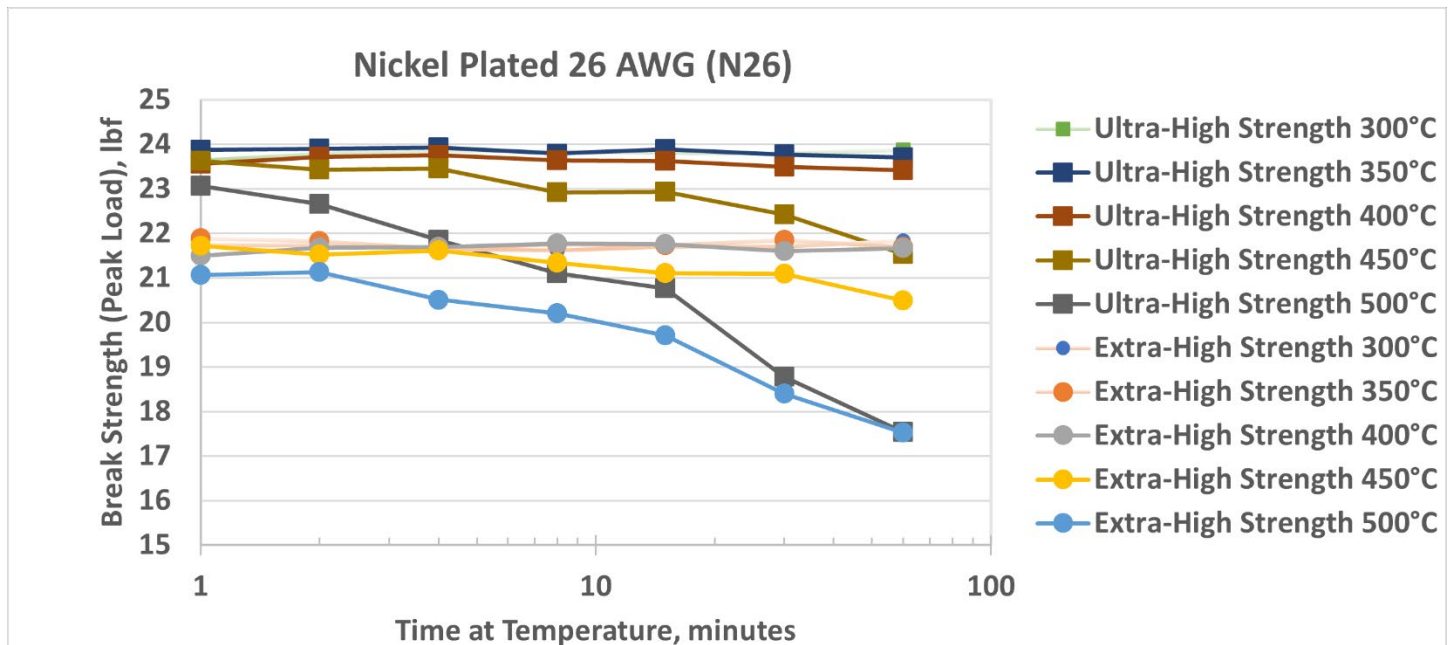


Figure 2 - Thermal softening behavior of nickel-plated 26 AWG ultrahigh strength and extra-high strength alloys

In summary, extra-high strength copper alloy demonstrated good high-temperature performance comparable to either high strength or ultrahigh strength copper alloys and shows opportunities to provide higher strength at elevated temperatures.

6.1.4 Flex Life

Method: AS6324, Flex Life

To eliminate variability, flex life values are reported relative to copper. Commercially available copper samples were obtained for testing that had the properties given in [Table 12](#). Since silver- and nickel-plated 24 AWG copper had very similar flex life, only a silver-plated copper sample at 26 AWG was used as the basis of comparison for the 26 AWG samples.

Table 12 - Properties of commercial copper samples used to establish flex life baseline

Alloy	Plate	AWG	Dia. in.	DCR Ω/mft	Wt. lb/mft	BL lbf	EL %
Cu	Silver	24	0.0230	23.9	1.38	12.9	19
Cu	Nickel	24	0.0232	24.3	1.39	14.8	19
Cu	Silver	26	0.0190	34.9	0.940	9.6	19

The results of the flex life testing of all eight samples are presented in [Figure 3](#). A total of 12 samples were tested for each sample. The average of the 12 samples was divided by the average flex life of the 12 copper samples to represent the relative flex life value. The samples are grouped for easy comparison to the reference alloy conductor of the given gauge size and coating type. It has been demonstrated that flex life correlates to the strength of the conductor, and it is therefore expected that extra-high strength copper alloy will have a higher flex life than high strength and lower flex life than ultrahigh strength. The consistency of relative results indicates the validity of the test and the consistency in the performance of the alloy. Extra-high strength provides a significant increase in flex life relative to the high strength alloy category, and even though it is lower than the comparative ultrahigh strength alloy, the relative performance to copper is still excellent.

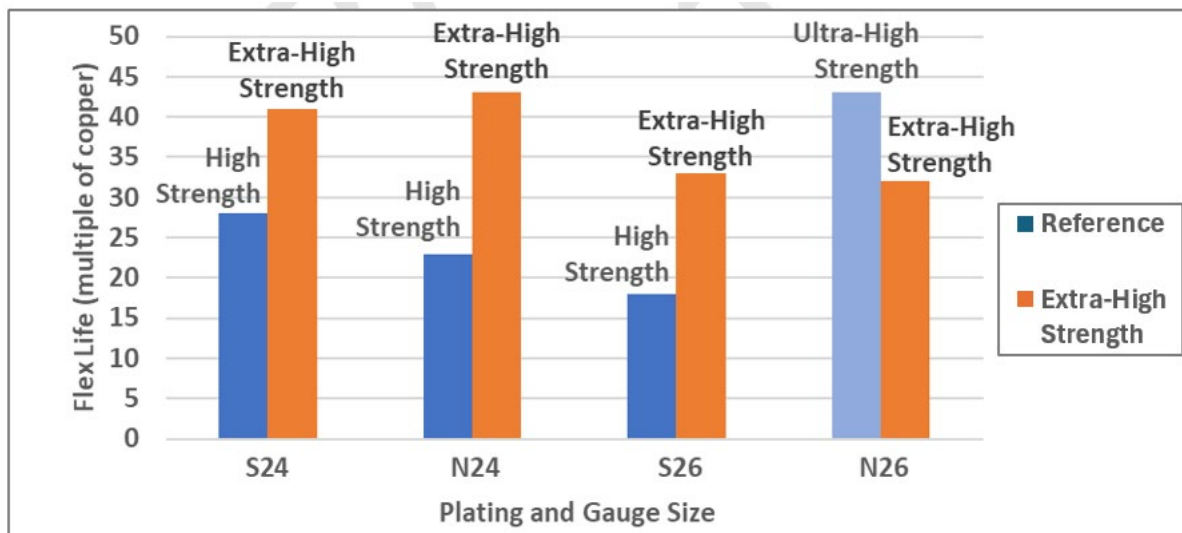
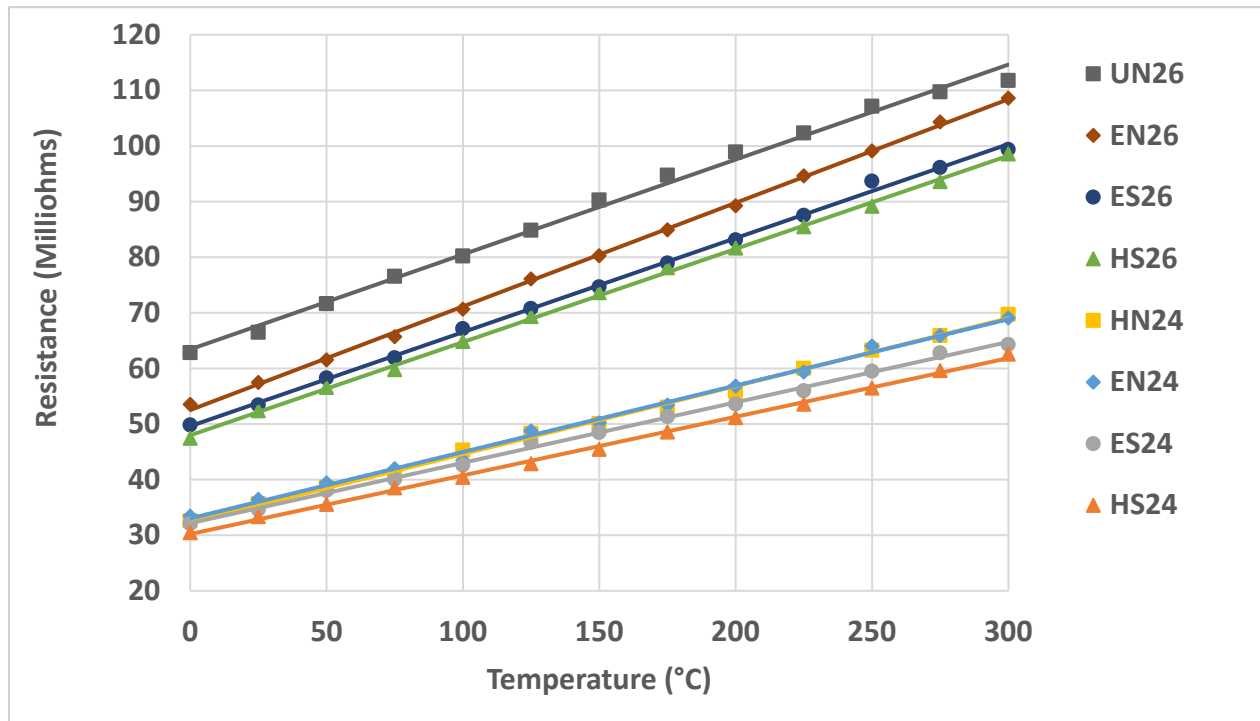


Figure 3 - Flex life presented relative to the flex life of copper

6.1.5 Temperature Coefficient of Resistance (TCR)

Method: AS6324, Temperature Coefficient of Resistance

Resistance as a function of temperature was measured from 0 to 300 °C for each conductor. The TCR was calculated from the slope of the line of best fit divided by the reference resistance using the plots of resistance versus temperature provided in [Figure 4](#). The resultant TCR values are listed in [Table 13](#). The plots demonstrate the consistency of the data indicating a quality test. The resultant TCR shows good self-consistency for the extra-high strength with a value of about .0034 for silver- and .0036 for nickel-plated samples. High strength and extra-high strength copper alloys have a similar TCR, while the TCR of high strength and extra-high strength is higher than ultrahigh strength copper alloy. The results show higher TCR value for alloys with higher electrical conductivity and are consistent with published TCR values for these alloys.

**Figure 4 - Resistance versus temperature between 0 and 300 °C****Table 13 - Temperature coefficient of resistance (TCR)**

Sample	TCR, α (1/°C)
HS24	0.00327
ES24	0.00338
HN24	0.00375
EN24	0.00358
HS26	0.00350
ES26	0.00340
UN26	0.00270
EN26	0.00355

6.1.6 Solderability (Silver-Plated)

Method: AS29606, Silver-Coated Conductor

Silver-plated samples were tested in accordance with MIL-STD-202, Method 208 except wrapping wire in accordance with J-STD-002. Test C is not necessary. Testing was performed by Lectromec and is detailed in Report number N1164-R001 Rev. B dated August 11, 2021, and Report number N1427-R001 dated December 14, 2021. All samples passed the solderability test.

6.2 Insulated Wire Results

The results of the required tests highlighted in [Table 5](#) are grouped in the as-insulated, thermally aged, thermal shocked, and after vibration conditioning below.

6.2.1 As-Insulated Wire

6.2.1.1 Wire Diameter and Weight

Method: AS4373, Method 901 and Method 902

Six diameter readings were taken on each of three samples for a total of 18 readings per wire. The results are summarized in [Table 14](#) listing average values. All measured diameters met their respective AS22759 specification sheet requirements. The most significant variance occurred between the UN26/82 and the EN26/94, where the extra-high strength copper alloy insulated wire averaged 0.0013 inch smaller than the ultrahigh strength insulated wire. Other than slight differences in the conductor diameter identified in conductor testing, the primary influencer of finished wire diameter is the application of the insulation system by the wire producer.

The finished weight of the insulated wire is a function of the conductor mass, insulation diameter, wall thickness, and density. The results are listed in [Table 14](#). Both the high strength (/33) and the extra-high strength copper alloy (/55) conformed to the weight requirement of the extruded wire. The results of the tape wrapped products (/82 and /94) also met the requirements. The specification for the extra-high strength copper alloy has a higher maximum weight requirement for both 24 gauge and 26 gauge versus the high strength copper alloy insulated wire. The high strength (/33), ultrahigh strength (/82), and the extra-high strength (/94) insulated wires conformed to their respective maximum weight requirement.

Table 14 - Wire diameter and weight

REF	ALLOY	COATING / PLATING	GAUGE	INSULATION	Diameter Inch	Weight lb/kft
HS24/33	High Strength	Silver	24	XL-ETFE	0.0368	1.892
ES24/55	Extra-High Strength	Silver	24	XL-ETFE	0.0359	1.884
HN24/82	High Strength	Nickel	24	PI/PTFE	0.0367	1.987
EN24/94	Extra-High Strength	Nickel	24	PI/PTFE	0.0365	2.001
HS26/33	High Strength	Silver	26	XL-ETFE	0.0324	1.336
ES26/55	Extra-High Strength	Silver	26	XL-ETFE	0.0327	1.373
UN26/82	Ultrahigh Strength	Nickel	26	PI/PTFE	0.0323	1.406
EN26/94	Extra-High Strength	Nickel	26	PI/PTFE	0.0310	1.377

6.2.1.2 Wire Strip Force

Method: AS4373, Method 103

A 0.25-inch insulation slug was stripped from the insulated wire with the AS5768 tool. The AS22759/33 and AS22759/55 had the insulation removed from one end of the wire only since these constructions have extruded insulation and there is no directionality to the insulation wall. Tables 15 and 16 provide the results of stripping these wires. The average removal force for all the samples was between 2.6 to 2.9 pounds. The results are typical of a well-applied insulation system. Values between 1 to 6 pounds are sufficient to keep the insulation well adhered to the conductor without risk of conductor splaying during insulation removal.

Table 15 - Strip force for 24 gauge extruded wire

Parameter	HS24/33				ES24/55		
	Sample #1	Sample #2	Sample #3		Sample #1	Sample #2	Sample #3
Gauge	24				24		
# Strands	19				19		
Insulation	XLETFE				XLETFE		
Insulation Type	Extruded				Extruded		
Insulation Thickness	0.007				0.007		
Wire Diameter	0.0365				0.0360		
Cond Diameter	0.023				0.023		
Hole Diameter	0.024				0.024		
Max Pull Force	2.501	2.415	2.961		2.855	2.808	2.944
Average	2.626				2.869		

Table 16 - Strip force for 26 gauge extruded wire

Parameter	HS26/33				ES26/55		
	Sample #1	Sample #2	Sample #3		Sample #1	Sample #2	Sample #3
Gauge	26				26		
# Strands	19				19		
Insulation	XLETFE				XLETFE		
Insulation Type	Extruded				Extruded		
Insulation Thickness	0.007				0.007		
Wire Diameter	0.0330				0.0330		
Cond Diameter	0.018				0.018		
Hole Diameter	0.019				0.019		
Max Pull Force	2.416	3.170	2.706		2.877	2.503	2.461
Average	2.764				2.614		

The tape wrap wires do have directionality due to the cross wrapping of the insulating materials. This creates directionality where stripping one end of the wire pulls the slug off in the direction of the tape, and on the other end the insulation is pulled against the direction of the tape. The strip force results for the tape wrap constructions are shown in Tables 17 and 18. For these samples both ends of the wire sample were evaluated for slug removal. The average removal force for all the samples was between 3.0 to 4.3 pounds. The results are typical of a well-applied insulation system. Values between 1 to 6 pounds are sufficient to keep the insulation well adhered to the conductor without risk of conductor splaying during insulation removal.

Table 17 - Strip force for 24 AWG tape wrap

Parameter	HN24/82			EN24/94		
	Sample #1	Sample #2	Sample #3	Sample #1	Sample #2	Sample #3
Gauge	24			24		
# Strands	19			19		
Insulation	PI/PTFE			PI/PTFE		
Insulation Type	Tape			Tape		
Insulation Thickness	0.005			0.006		
Wire Diameter	0.0370			0.0370		
Cond Diameter	0.024			0.024		
Hole Diameter	0.025			0.025		
Max Pull Force #1	3.101	3.168	3.690	3.963	3.839	5.096
Max Pull Force #2	3.059	3.265	3.065	3.700	4.035	5.089
Average	3.225			4.287		

Table 18 - Strip force for 26 AWG tape wrap

Parameter	UN26/82			EN26/94		
	Sample #1	Sample #2	Sample #3	Sample #1	Sample #2	Sample #3
Gauge	26			26		
# Strands	19			19		
Insulation	PI/PTFE			PI/PTFE		
Insulation Type	Tape			Tape		
Insulation Thickness	0.006			0.006		
Wire Diameter	0.0320			0.0310		
Cond Diameter	0.019			0.019		
Hole Diameter	0.020			0.020		
Max Pull Force #1	3.588	3.676	3.097	3.291	2.778	3.111
Max Pull Force #2	2.954	4.557	4.182	3.083	2.853	2.791
Average	3.676			2.985		

6.2.1.3 Center-of-Wire Tensile Strength

Method: AS6324, Center-of-Wire Tensile Strength

The break strength of extra-high strength conductors should be higher than the high strength conductor class and lower than the ultrahigh strength conductor class. This test examines the strength of the conductor following insulation.

Tables 19 and 20 provide the results of the evaluation for the extruded wire and tape wrap wire, respectively. For the extruded products, the ES24/55 wire averaged 32.1 pounds more (25% greater) than the HS24/33 with a 25.6-pound average. The 55P26S26 wire averaged 20.8 pounds more (39% greater) than the HS26/33 with an average of 16.0 pounds.

For the tape wrapped products, the EN24/94 wire averaged 31.7 pounds more (24% greater) than the HN24/82 high strength wire with an average of 25.5 pounds. The EN26/94 wire averaged 18.8 pounds less (17% lower) than the UN26/82 ultrahigh strength copper alloy with an average of 22.6 pounds.

Based on the results of the 24 gauge evaluation, which is a direct comparison between high strength and extra-high strength copper alloys using extruded, and tape wrapped insulation, there is no discernible difference in center of wire break strength between the different insulation systems.

Table 19 - Center of wire tensile strength (break load in lbf) (extrusion)

Parameter	XLETFE (Extrusion)			
	HS24/33	ES24/55	HS26/33	ES26/55
Test Speed	1	1	1	1
Sample #1	26.1	32.0	15.7	20.7
Sample #2	25.2	32.1	16.5	20.8
Sample #3	25.5	32.1	15.9	20.8
Tensile pounds	25.6	32.1	16.0	20.8

Table 20 - Center of wire tensile strength (break load in lbf) (tape wrap)

Parameter	Polyimide/PTFE (Tape Wrap)			
	HN24/82	EN24/94	UN26/82	EN26/94
Test Speed	1	1	1	1
Sample #1	25.4	32.0	21.9	18.9
Sample #2	25.5	32.4	22.5	19.6
Sample #3	25.7	30.8	23.3	18.0
Tensile pounds	25.5	31.7	22.6	18.8

6.2.1.4 Center of Wire Flex Life

Method: AS6324, Center of Wire Flex Life

Center of wire flex life is a function of both the conductor tensile strength and insulation system. Previous OEM studies have demonstrated that the polyimide/PTFE insulation system better protects the conductor from strand breakage versus the extruded insulations. Also, it has been shown that conductors with higher tensile strength have better flex life. This evaluation not only examined flex life to failure, but it also examined the rate of conductor breakage as a function of percentage of flex life cycles. This test examined two samples at 50%, 60%, 70%, 80%, and 90% of average flex life for broken strands.

[Table 21](#) displays the results of the four extruded wire constructions. For the 24 gauge wires, the extra-high strength wire, ES24/55, averaged 2118 cycles, or 210% greater than the high strength wire, HS24/33, which averaged 683 cycles. For the 26 gauge wires, the ES26/55 wire averaged 1445 cycles, or 410% greater than the HS26/33 wire, which averaged 283 cycles.

Table 21 - Center of wire flex life of extruded wires

Wire	HS24/33	ES24/55	HS26/33	ES26/55
Avg. Flex Life	683	2118	283	1445

[Table 22](#) provides the results of cyclic flexing for the HS24/33 wire. At 50%, none of the samples had any broken strands. At 60%, one sample had three broken strands and the other had five broken strands. At 70%, one sample had one broken strand and the other had three broken strands. At 80%, both wires had complete rupture, 19 broken strands. At 90%, one wire had complete rupture, 19 broken strands, while the other had 12 broken strands.

Table 22 - Number of broken strands versus percentage of flex life, HS24/33

Sample	% Baseline	# Cycles	Broken	Rupture	# of Cycles
Sample #1	50	342	0	NO	N/A
Sample #2	50	342	0	NO	N/A
Sample #3	60	410	3	NO	N/A
Sample #4	60	410	5	NO	N/A
Sample #5	70	478	3	NO	N/A
Sample #6	70	478	1	NO	N/A
Sample #7	80	546	19	YES	480
Sample #8	80	546	19	YES	541
Sample #9	90	615	19	YES	615
Sample #10	90	615	12	NO	N/A

[Table 23](#) provides the results of cyclic flexing for the ES24/55 wire. At 50% and 70%, neither sample had any broken strands. At 60%, one wire had one broken strand while the other sample had none. At 80%, one sample had three broken strands while the other had none. At 90%, one sample had four broken strands while the other had none. This construction demonstrated significantly fewer broken wires than the same construction using high strength copper alloy in 24 gauge.

Table 23 - Number of broken strands versus percentage of flex life, ES24/55

Sample	% Baseline	# Cycles	Broken	Rupture	# of Cycles
Sample #1	50	1059	0	NO	N/A
Sample #2	50	1059	0	NO	N/A
Sample #3	60	1271	0	NO	N/A
Sample #4	60	1271	1	NO	N/A
Sample #5	70	1483	0	NO	N/A
Sample #6	70	1483	0	NO	N/A
Sample #7	80	1695	1	NO	N/A
Sample #8	80	1695	3	NO	N/A
Sample #9	90	1906	0	NO	N/A
Sample #10	90	1906	4	NO	N/A

[Table 24](#) provides the results of cyclic flexing for the HS26/33 wire. At 50%, neither sample had any broken strands. At 60%, one sample had one broken strand and the other had none. At 70%, one sample had nine broken strands while the other had 11 broken strands. At 80%, one sample had four broken strands while the other sample had ten broken strands and the other sample had three broken strands. At 90%, one sample had complete rupture (19 broken strands), while the other sample had 13 broken strands.

Table 24 - Number of broken strands versus percentage of flex life, HS26/33

Sample	% Baseline	# Cycles	Broken	Rupture	# of Cycles
Sample #1	50	142	0	NO	N/A
Sample #2	50	142	0	NO	N/A
Sample #3	60	170	1	NO	N/A
Sample #4	60	170	0	NO	N/A
Sample #5	70	198	9	NO	N/A
Sample #6	70	198	11	NO	N/A
Sample #7	80	227	4	NO	N/A
Sample #8	80	227	10	NO	N/A
Sample #9	90	255	19	YES	235
Sample #10	90	255	13	NO	N/A

[Table 25](#) provides the results of cyclic flexing for the ES26/55 wire. At 50% and 60%, neither sample had any broken strands. At 70%, both samples had one broken strand. At 80%, one sample had one broken strand and the other had three broken strands. At 90%, one sample had five broken strands, while the other sample had four broken strands. This construction demonstrated significantly fewer broken strands than the same construction using high strength copper alloy in 26 gauge.

Table 25 - Number of broken strands versus percentage of flex life, ES26/55

Sample	% Baseline	# Cycles	Broken	Rupture	# of Cycles
Sample #1	50	722	0	NO	N/A
Sample #2	50	722	0	NO	N/A
Sample #3	60	867	0	NO	N/A
Sample #4	60	867	0	NO	N/A
Sample #5	70	1011	1	NO	N/A
Sample #6	70	1011	1	NO	N/A
Sample #7	80	1156	1	NO	N/A
Sample #8	80	1156	3	NO	N/A
Sample #9	90	1300	5	NO	N/A
Sample #10	90	1300	4	NO	N/A

[Table 26](#) displays the results of the four tape wrap wire constructions. For the 24 gauge wires, the extra-high strength wire, EN24/94, averaged 1808 cycles, or 76% greater than the high strength wire, HN24/82, which averaged 1025 cycles. For the 26 gauge wires, the EN26/94 wire averaged 1499 cycles, or 16% lower than the UN26/82 wire, which averaged 1773 cycles. Again, extra-high strength wires show a greater flex life than the high strength alloy high strength wires.

Table 26 - Center of wire flex life of tape wrap wires

Wire	HN24/82	EN24/94	UN26/82	EN26/94
Avg. Flex Life	1025	1808	1773	1499

[Table 27](#) provides the results of cyclic flexing for the HN24/82 wire. At 50%, neither sample had any broken strands. At 60%, one sample had four broken strands. At 70%, one sample had one broken strand and the other had three broken strands. At 80%, one sample had one broken strand and the other had none. At 90%, one sample had two broken strands and the other had seven broken strands.

Table 27 - Number of broken strands versus percentage of flex life, HN24/82

Sample	% Baseline	# Cycles	Broken	Rupture	# of Cycles
Sample #1	50	512	0	NO	N/A
Sample #2	50	512	0	NO	N/A
Sample #3	60	615	0	NO	N/A
Sample #4	60	615	4	NO	N/A
Sample #5	70	717	1	NO	N/A
Sample #6	70	717	3	NO	N/A
Sample #7	80	820	0	NO	N/A
Sample #8	80	820	1	NO	N/A
Sample #9	90	922	2	NO	N/A
Sample #10	90	922	7	NO	N/A

[Table 28](#) provides the results of cyclic flexing for the tape wrap extra-high strength wire, EN24/94. At 50%, 60%, 70%, and 80%, none of the samples had any broken strands. At 90%, one sample had two broken strands and the other had one broken strand.

Table 28 - Number of broken strands versus percentage of flex life, EN24/94

Sample	% Baseline	# Cycles	Broken	Rupture	# of Cycles
Sample #1	50	904	0	NO	N/A
Sample #2	50	904	0	NO	N/A
Sample #3	60	1085	0	NO	N/A
Sample #4	60	1085	0	NO	N/A
Sample #5	70	1266	0	NO	N/A
Sample #6	70	1266	0	NO	N/A
Sample #7	80	1447	0	NO	N/A
Sample #8	80	1447	0	NO	N/A
Sample #9	90	1627	1	NO	N/A
Sample #10	90	1627	2	NO	N/A

[Table 29](#) provides the results of cyclic flexing for the UN26/82 wire. At 50%, 60%, 70%, and 80%, none of the samples had any broken strands. At 90%, one sample had two broken strands and the other had one broken strand. The number of broken strands using the tape wrap product was less than the number using the extruded product.