824.0 kcmil ACCR Overhead Conductor Tensile Tests

NEETRAC Project: 24-151

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Requested by: Idaho National Labs (INL)

Principal Investigator: Joe Goldenburg, PE

Co-Principal Investigator: Paul Springer, PE

Reviewed by: Joe Goldenburg, PE

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NEETRAC Project 24-151

1.0 BACKGROUND

An overhead conductor is an assembly of conductive strands, typically aluminum or aluminum alloy. Most designs incorporate a high strength core, which is typically steel but composite materials are gaining in popularity. Regardless of steel or composite, a core can be a single strand or multi-strand. Conductor specifications are computed based on a weighted average of the properties of each component.

Caveat: conductor Standards require manufacturer agreement to apply the component acceptance criteria to strands removed from a finished conductor. This is because properties change during manufacturing, and the acceptance criteria therefore apply only before manufacturing. Since these tests are performed after manufacturing, the individual strand tests should be considered “for information only”.

2.0 TEST SAMPLES

Test samples were removed from a reel provided by the Western Area Power Administration (WAPA) through INL circa January 2025. The designation on the reel identified the conductor as 824.0 kcmil ACCR. The following samples were prepared under this project:

2.1 Individual Strands:

Three (3) samples, each three (3) ft long were cut from the reel and unstranded. Each strand was tagged to document its location in the original conductor. The individual strands were subjected to tensile tests.

2.2 Complete Core:

A new sample was not required. A 22-ft sample from the recent stress-strain test was pulled to destruction. That data is reported in the stress-strain test report, and repeated in this report in the interest of having a single reference for tensile test results.

2.3 Complete Conductor:

The original scope envisioned only one complete conductor tensile test. The scope was broadened to ensure an accurate determination of the rated breaking strength using laboratory terminations. Three (3) samples, each 12 ft long, one (1) 22 ft long, and one (1) sample 10 ft long were tested. The short sample was a qualification test for the lab terminations.

3.0 PROCEDURE

3.1 Dimensions

Aluminum strands: Diameters were measured in three evenly-spaced directions, and the measurements averaged. After finding non-compliant results, these measurements were cross-checked using the mass method of ASTM B263. A precise length measurement, weight measurement, and the nominal density are used to compute the area and impute the diameter. The two methods were found to be in good agreement. For additional confirmation, two variants of the mass method were used: one on straightened individual strands and one on the complete conductor (strands in the helix shape) with the manufacturer's nominal stranding factor used to correct for the additional length of the helix shape. As additional due diligence, both the micrometer measurements and the mass method tests were repeated independently by a 2^{nd} technician. The agreement among the three methods and two individuals was within 0.2%. This confirms the finding that the aluminum strand area averages 4% below the nominal area, and 2% below the minimum allowable area.

Core strands: ASTM B976 provides core strand tensile ratings in lb, and not the normalized tensile strength in psi. Diameter measurements were not needed and not performed.

3.2 Tensile/Elongation

Aluminum strands: tensile/elongation testing was in accordance with ASTM B941 (Al-Zr aluminum alloy strands), with the exception that the strands were tested after manufacturing. Prior to testing, each strand was straightened by rolling it on a flat steel surface, and using a long softwood timber (2 x 4) to flatten the curvature. A precise 10.000 inch gage section is marked on the sample. Vee-wedge grips are used for the tensile test. See Figure 1 for the aluminum strand test.

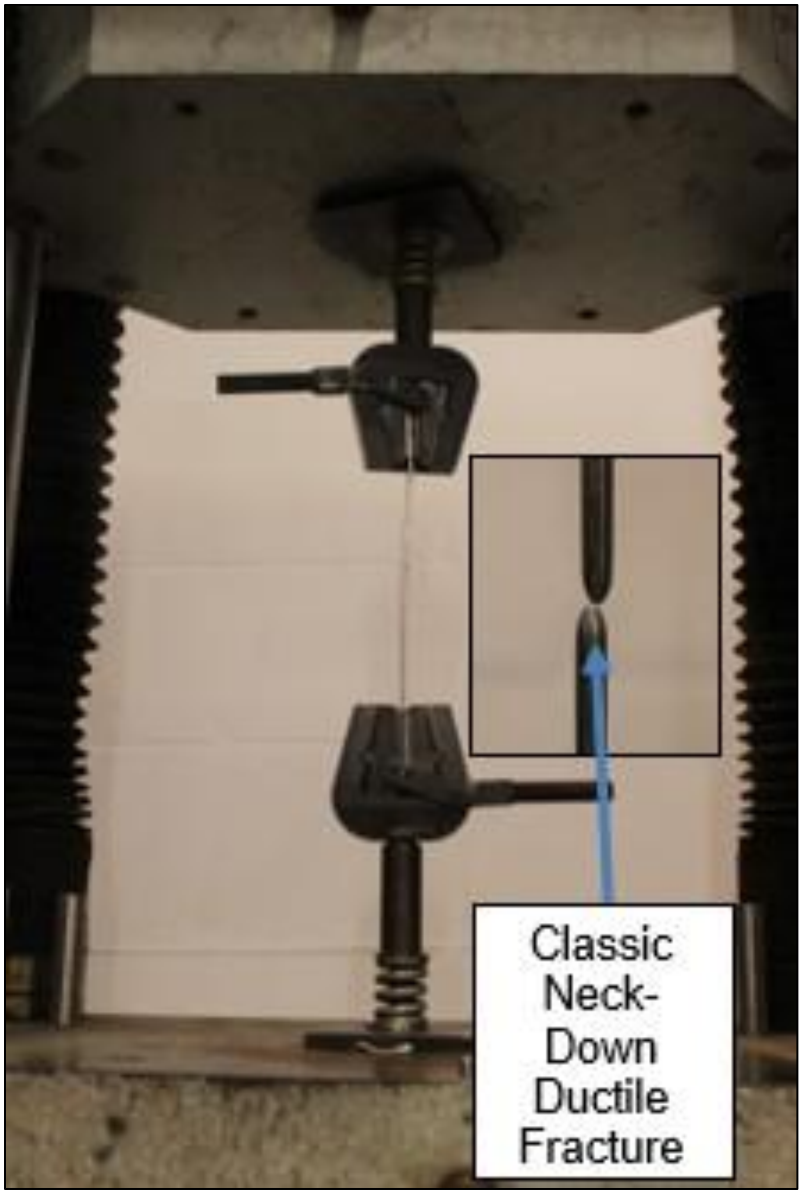

Figure 1: Vee-wedge grips with 3M strand

Core strands: tensile testing was in accordance with ASTM B976 (aluminum matrix composite (AMC) core strands). Samples were cut to 3-ft lengths. Six (6) inches at each end were potted into a stainless steel tube to prevent the wedge grips from damaging the composite strand. The Standard does not prohibit the application of the acceptance criteria to samples after stranding. AMC strands do not require straightening. See Figure 2 for the gripping arrangement for the MMC core strands.

Figure 2: AMC core strand potted in stainless steel tube for testing

4.0 RESULTS

4.1 Dimensions:

Diameter: The mean of the data from the direct micrometer measurement and the mass method differs by just 0.0003 in. See Figure 3 for a box plot of the actual data points. Table 1 shows the statistics for the dimension data.

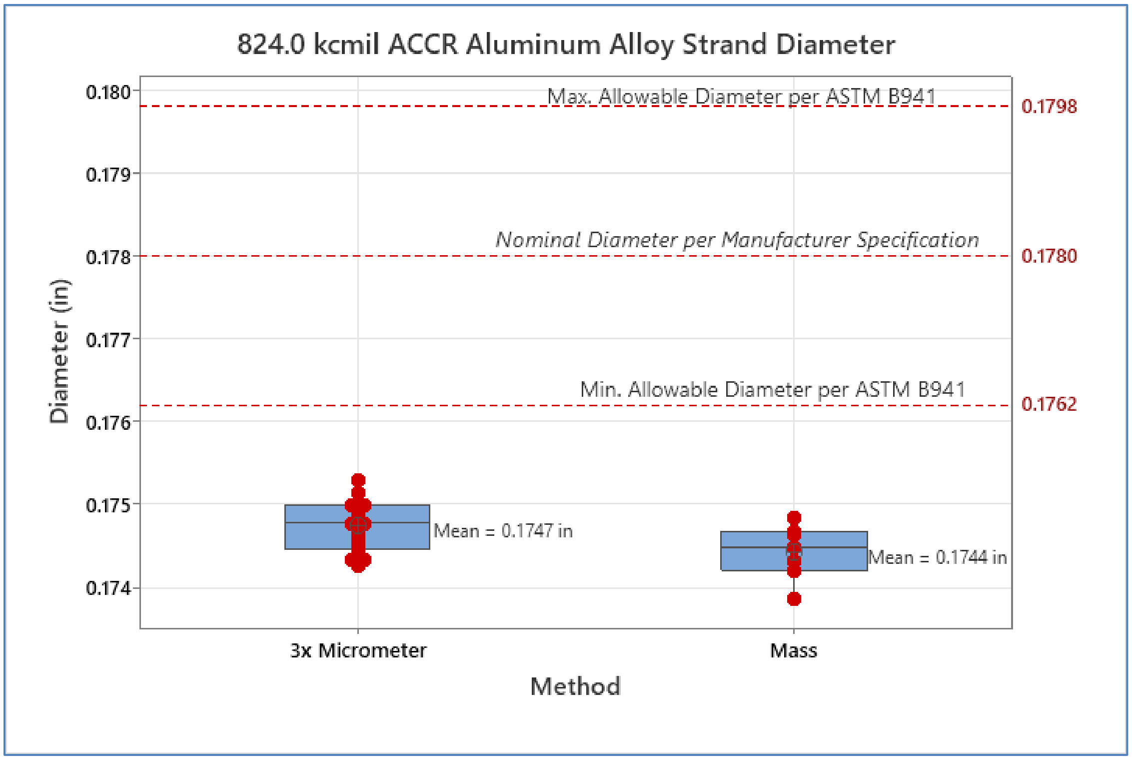

Figure 3: Diameter Data from Micrometer and Mass Methods

The mass method computes the area directly, and the round diameter is inferred from the area. The micrometer method measures the diameter directly, and the area is computed using the familiar πr^2 formula.

The nominal conducting area (824.0 kcmil) is computed using the nominal strand diameter from the product specification. The kcmil unit still in use for conducting area dates from a pre-computer age when slide rules performed convenient x^2 calculations. The area in circular mils (cmil) is simply (diameter in mil)^2. Nominal and actual conducting areas are computed thus:

Nominal conducting area: 26 strands x (178.0 mil)^2 /1000 = 823.9 kcmil.

Conducting area, mass method: 26 strands x (174.4 mil)^2 /1000 = 790.8 kcmil.

Conducting area, micrometer method: 26 strands x (174.7 mil)^2 /1000 = 793.5 kcmil

ASTM B979 (ACCR conductors) states that the conducting area "…shall not be less than 98% of the area specified." The standard states that the mass method is authoritative. The actual conducting area computed using the authoritative mass method is 96.0% of the "area specified." This means that all other factors equal, line loss during the service life of the conductor is 4% greater than a conductor meeting the nominal area requirement, and 2% greater than a conductor meeting the minimum area requirement. The computation of the rated breaking strength is based upon the <u>nominal</u> area, meaning the contribution from the aluminum alloy component is 4% below expectations.

Table 1 shows the statistics for the diameter data, including the two technician effects.

Table 1 Statistics for Aluminum Strand Diameter Data

Results for Method = 3x Micrometer, Layer = Inner

Statistics

Variable	Tech.	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median
Avg Diameter (in)	1	5	0	0.17472	0.0001096	0.0002451	0.17435	0.174483	0.1748
	2	5	0	0.17473	0.0001081	0.0002416	0.174433	0.174483	0.174767

Variable	Tech.	Q3	Maximum
Avg Diameter (in)	1	0.174917	0.174983
	2	0.174958	0.174983

Results for Method = 3x Micrometer, Layer = Outer

Statistics

Variable	Tech.	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median
Avg Diameter (in)	1	5	0	0.17483	0.0001595	0.0003568	0.174333	0.1745	0.174867
	2	5	0	0.1747	0.0001774	0.0003967	0.17425	0.174292	0.174767

Variable	Tech.	Q3	Maximum
Avg Diameter (in)	1	0.175142	0.175283
	2	0.175075	0.175133

Results for Method = Mass, Layer = Inner

Statistics

Variable	Tech.	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median
Avg Diameter (in)	2	3	0	0.174124	0.0001336	0.0002314	0.173865	0.173865	0.174196

Variable	Tech.	Q3	Maximum
Avg Diameter (in)	2	0.174310	0.174310

Results for Method = Mass, Layer = Outer

Statistics

Variable	Tech.	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median
Avg Diameter (in)	2	4	0	0.174650	0.0000729	0.0001458	0.174475	0.174512	0.174647

Variable	Tech.	Q3	Maximum
Avg Diameter (in)	2	0.174790	0.174828

4.2 Tensile/Elongation

Core Strand Tensile:

Figure 4 shows the tensile test data points. Four samples failed in the gage section, the gold standard for a tensile test. Four samples failed in the grip and could be considered non-representative.

Table 2 shows the statistics for the core strand tensile data with the grip breaks omitted. The core demonstrates compliance with the manufacturer's breaking strength specification.

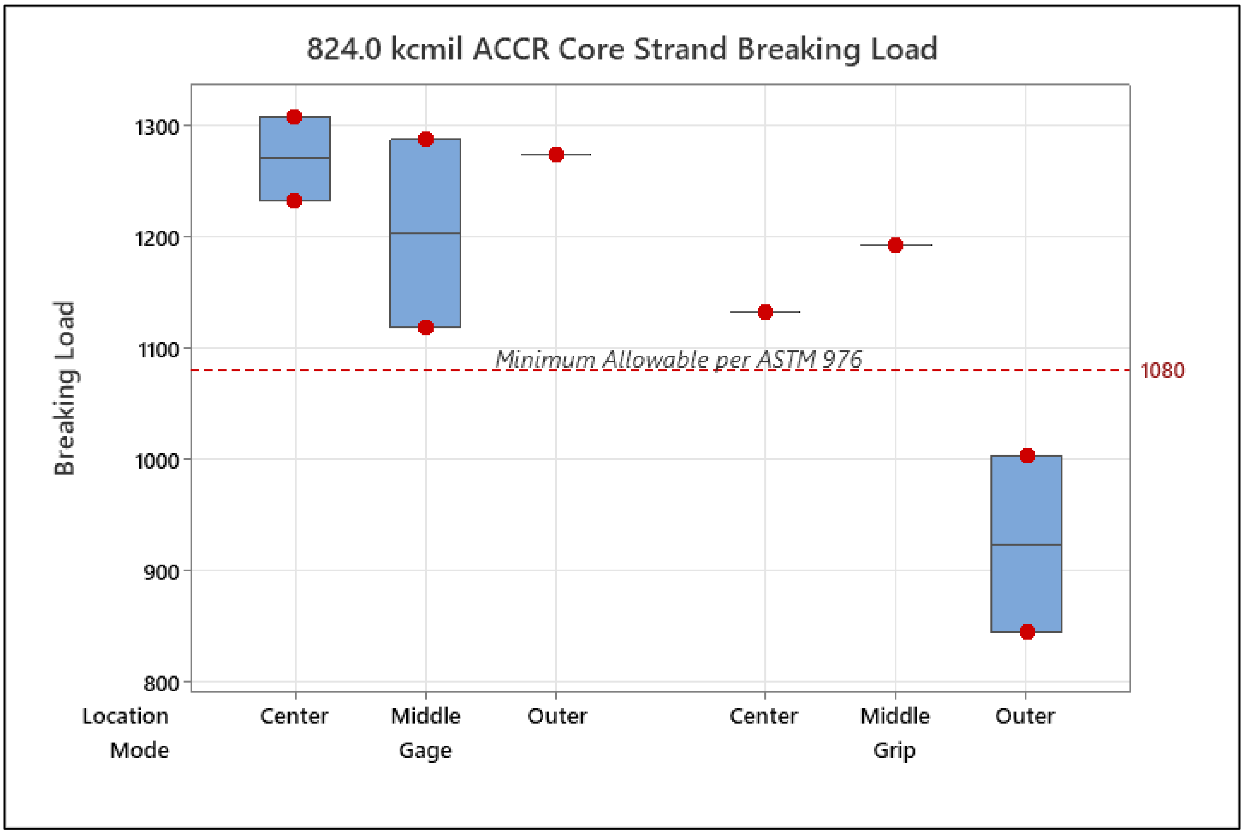

Figure 4: Core Strand Tensile Test Data

An elongation measurement is not practical, and not required for the near-zero-elongation MMC core strands.

Table 2 Statistics for Core Strand Tensile Test Data

Statistics

Variable	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
Breaking Load	9	0	1154.8	50.4	151.3	845.3	1060.8	1192.3	1280.5	1308.2

Results for Location = Center

Statistics

Variable	Mode	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
Breaking Load	Gage	2	0	1270.2	38.1	53.8	1232.1	*	1270.2	*	1308.2
	Grip	1	0	1132.7	*	*	1132.7	*	1132.7	*	1132.7

Results for Location = Middle

Statistics

Variable	Mode	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
Breaking Load	Gage	2	0	1202.6	84.4	119.4	1118.2	*	1202.6	*	1287.0
	Grip	1	0	1192.3	*	*	1192.3	*	1192.3	*	1192.3

Results for Location = Outer

Statistics

Variable	Mode	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3	Maximum
Breaking Load	Gage	1	0	1273.9	*	*	1273.9	*	1273.9	*	1273.9
	Grip	2	0	924.3	79.0	111.7	845.3	*	924.3	*	1003.3

<u>Aluminum Strand Tensile:</u>

Figure 5 shows the aluminum strand breaking strength data.

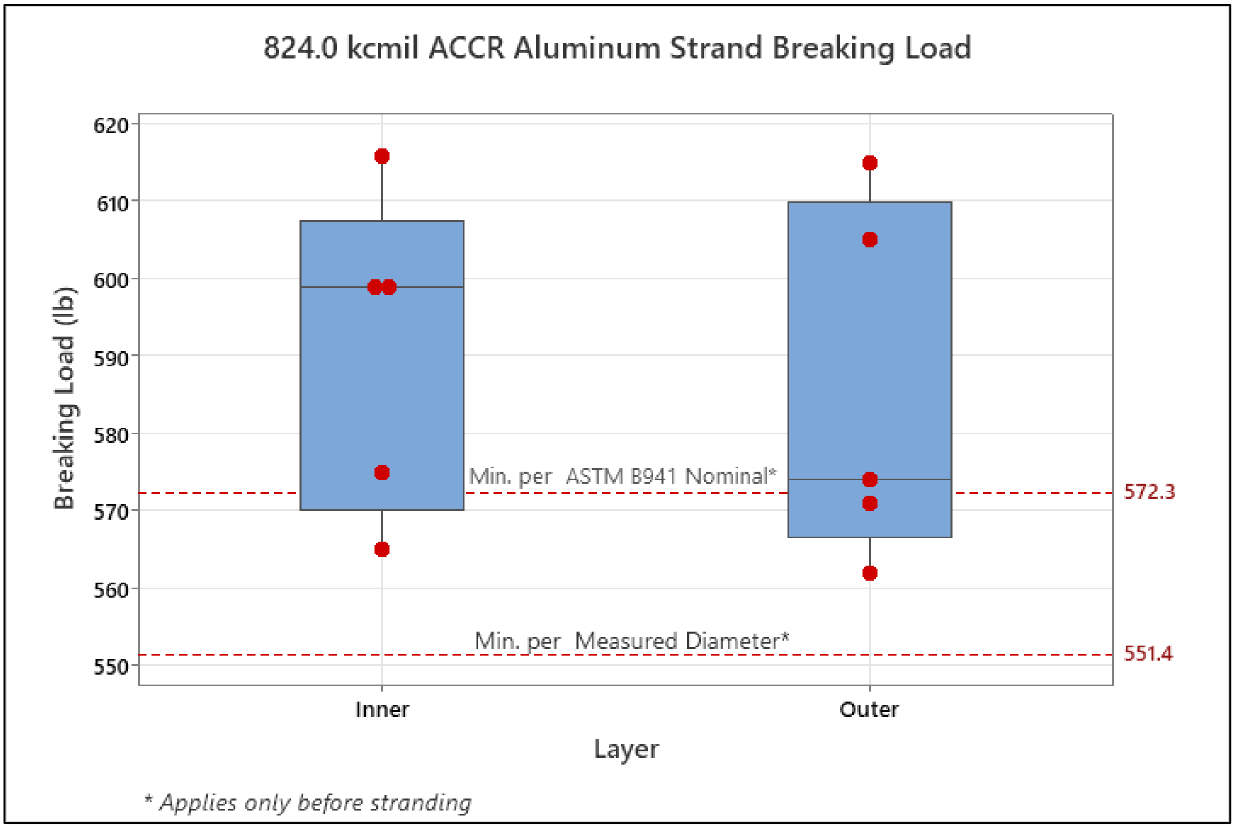

Figure 5: Aluminum Strand Breaking Strength Data

ASTM B978 requires a normalized tensile strength of 23.0 kpsi for a nominal 0.1780 in strand. Stranding mill QC departments typically base acceptance on the breaking load divided by the measured area. The conductor ratings are computed using the breaking strength divided by the nominal area. This is a trivial issue if the strand sizes are normally distributed around the nominal size. There are implications for conductor tensile strength and line losses if the strand sizes are consistently below nominal.

Figure 5 shows both acceptance criteria, one based on the nominal area and one based on the measured (actual) area.

Table 3 shows the statistics for the breaking strength data

Table 3 Statistics for Aluminum Strand Breaking Strength

Statistics

Variable	Layer	N	N*	Mean	SE Mean	StDev	Minimum	Q1	Median	Q3
Breaking Load (lb)	Inner	5	8	590.8	9.17824	20.5232	565	570	599	607.5
	Outer	5	9	585.4	10.3566	23.1582	562	566.5	574	610

Variable	Layer	Maximum
Breaking Load (lb)	Inner	616
	Outer	615

Figure 6 shows the normalized tensile strength computed using the <u>measured</u> diameter. Figure 7 shows the normalized tensile strength computed using the <u>nominal</u> diameter.

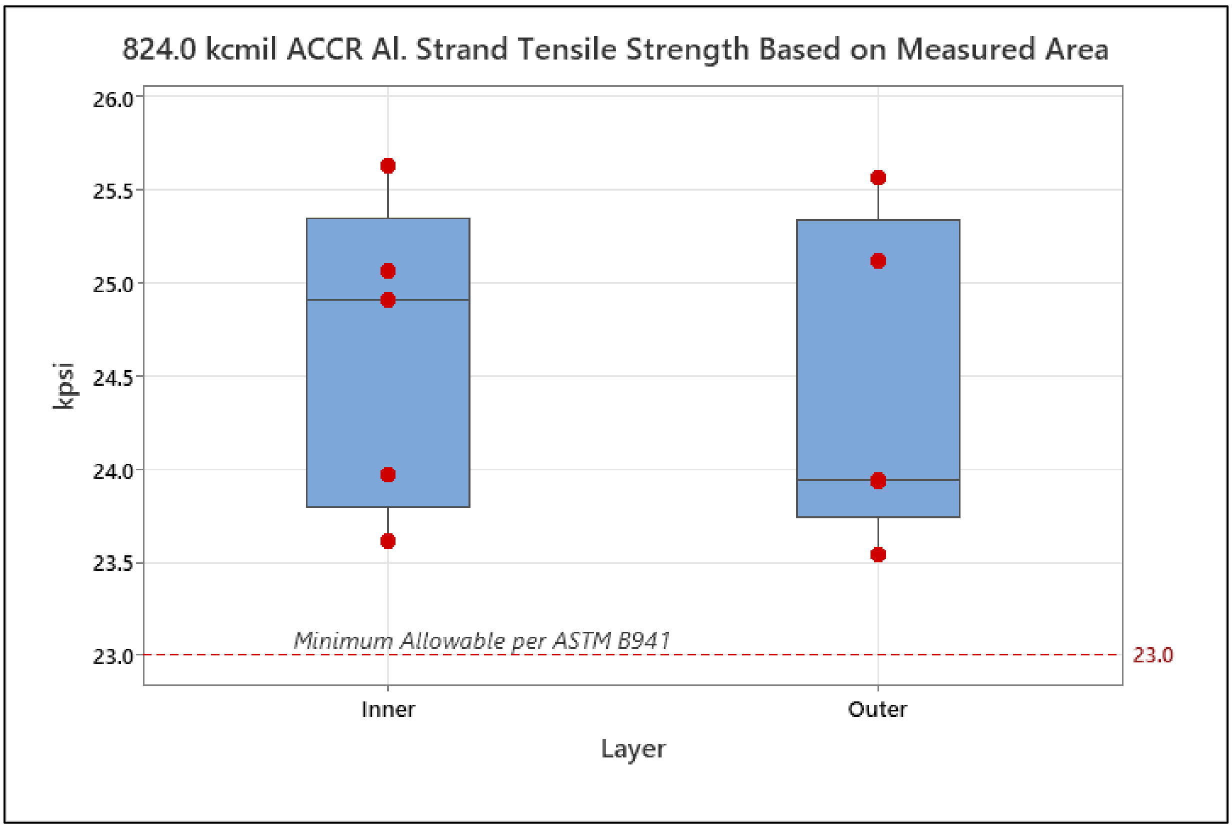

Figure 6: Tensile Strength Computed using the Measured Strand Area

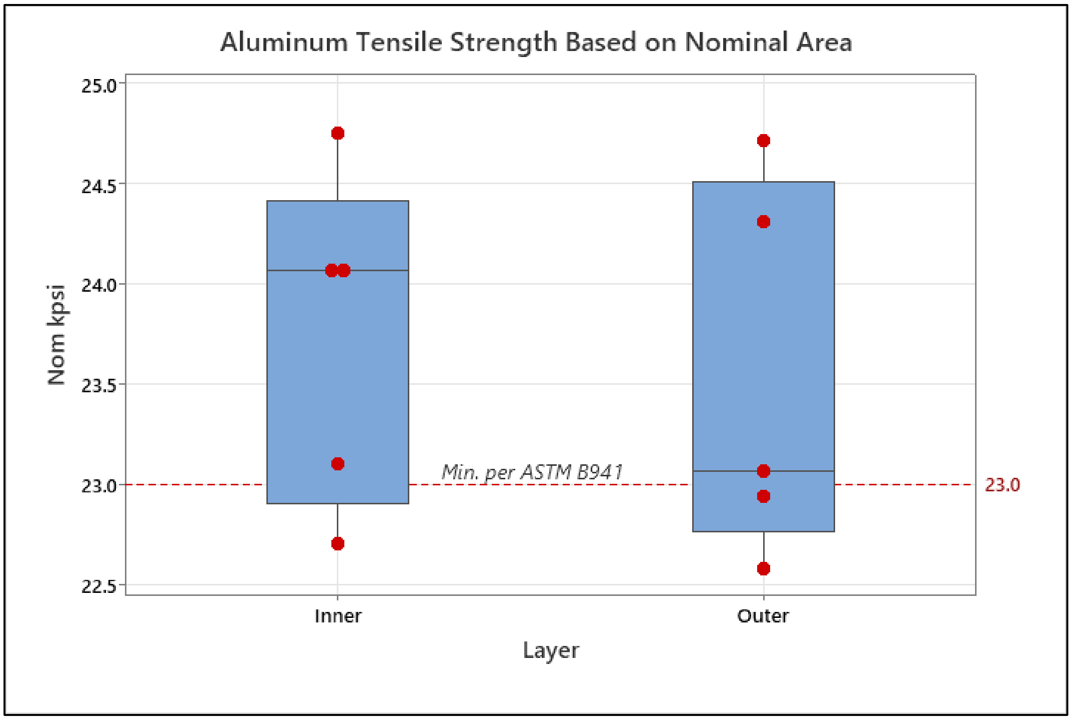

Figure 7: Tensile Strength Computed Using the Nominal Strand Area

Elongation (Aluminum Strands Only)

Figure 8 shows the elongation data for the sample of aluminum strands tested. All strands comfortably exceed the minimum requirement.

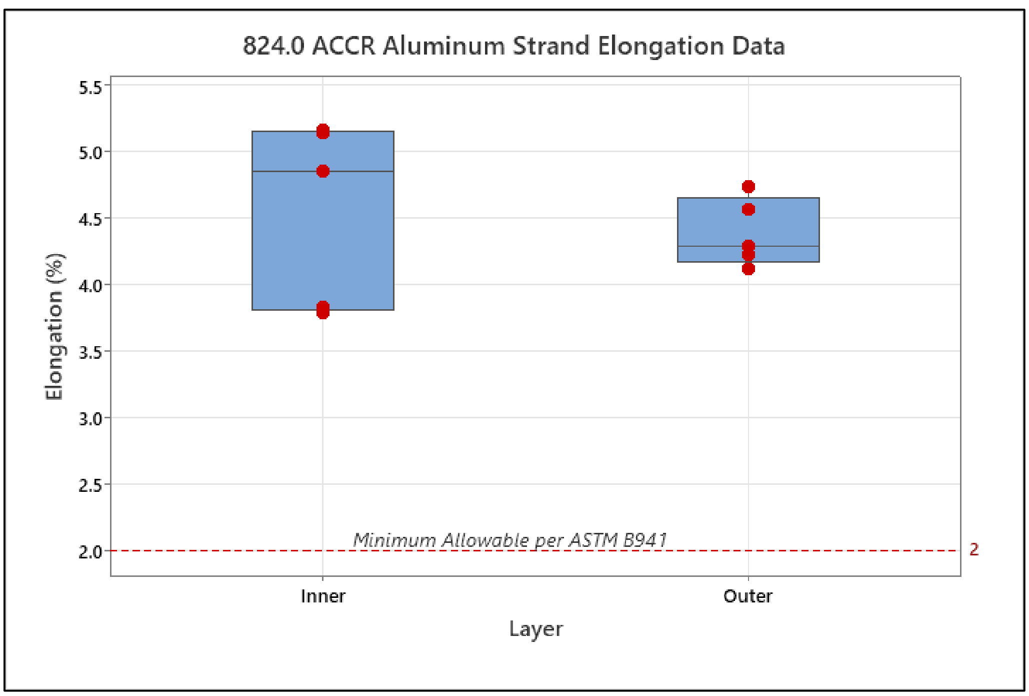

Figure 8: Aluminum Strand Elongation Data

4.3 Conductor Breaking Strength:

Ratings for conductor strength are based on calculations using the required minimum strength and the nominal dimensions of the constituent materials. The rated breaking strength (RBS) is a weighted average of the strength of the individual strands multiplied by rating factors designed to account for degradation from stranding.

Breaking strength may be estimated based on the measured strength of individual strands, and the application of the same weighted constituent contribution and stranding factors used in the applicable specification. The brute force method is to pot all strands into a laboratory socket, and pull the complete conductor to break. Both methods are reported here:

Strand Strength Method:

Nominal Rating: ASTM B978 (ACCR conductor) defines the rated strength of the conductor as:

Aluminum alloy: minimum tensile strength x nominal wire area x 0.967 x number of strands x derating factor. The aluminum derating factor for 26/19 stranding is 0.93.

Core: average strength of the core strands x number of strands x derating factor. The core derating factor for 26/19 stranding is 0.92.

Accordingly, the rated strength is:

Aluminum: 23,000 psi x 0.2488 in^2 x 0.967 x 26 strands x 0.93 =	13,383 lb
Core: 1080 lb x 19 strands x 0.92 =	18,878 lb
Total: (ratings are rounded to the nearest 100 lb) =	**32,300 lb**

The published rating is 32,200 lb, which agrees with this calculation other than a small truncation error.

Strength computed using individual-strand test data from this report:

Aluminum: 588.1 lb mean strength x 0.967 x 26 strands x 0.93 =	13,750 lb
Core: 1154.8 lb mean breaking strength x 19 strands x 0.92 =	20,186 lb
Total:	**33,900 lb (105% RBS)**

Tensile Test of Complete Conductor and Complete Core:

19-Strand Complete Core: The core sample from the stress-strain test was pulled to break after stress-strain data was recorded. The sample ruptured at the resin cone at 18,813 lb, or 99.7% of the nominal rating. Figure 9 shows the core data plotted against the actuator position.

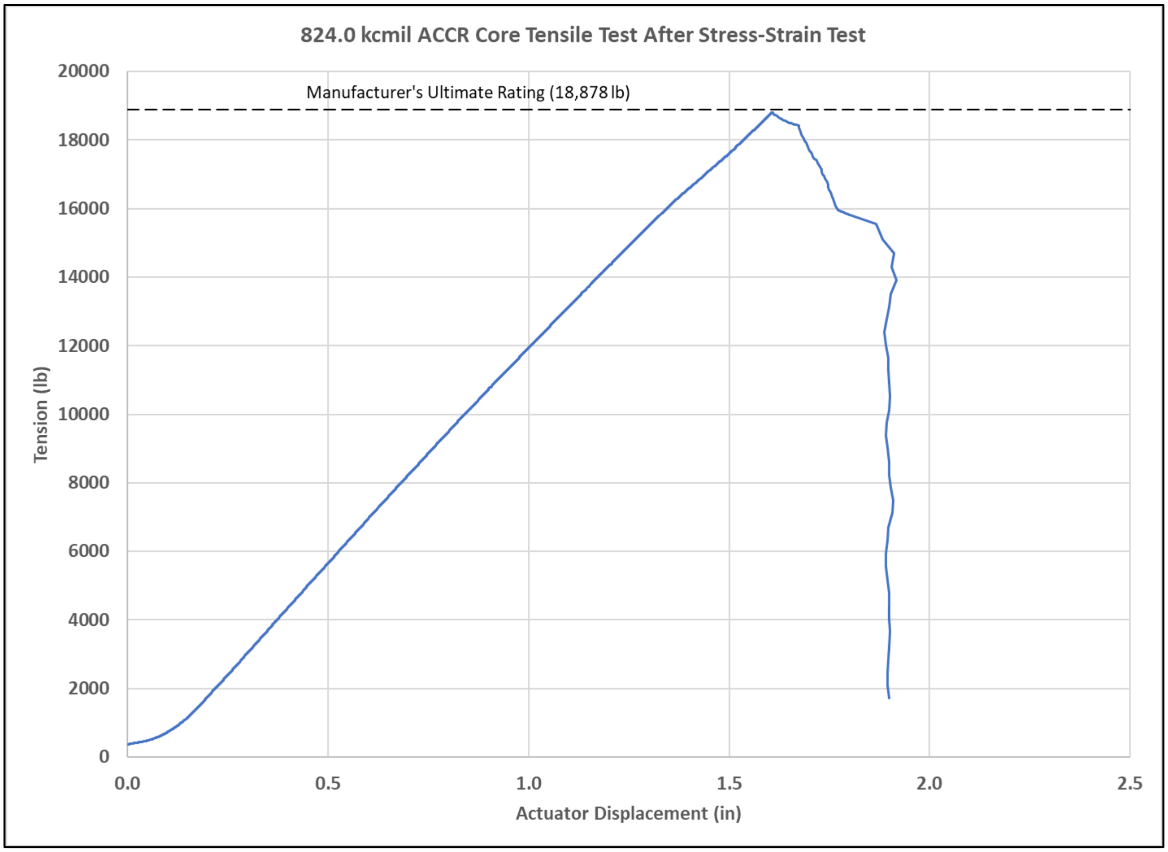

Figure 9: Tensile Test Data for the Complete 19-Strand Core

<u>Complete Conductor:</u> five (5) complete conductor samples were tested:

1. One (1) ten-foot sample tested to qualify the lab terminations.
2. One (1) 22-ft sample.
3. Three (3) 12-ft samples

Figure 10 shows the data for all five complete conductor tests. None of the samples reached the rated strength. Two (2) samples failed in the gage section, which is the gold standard for a tensile test. Three samples failed at the resin cone. Two of the resin cones were cut at the narrow end, middle, and wide end to observe for strand placement and any slipped strands. No slipped or broken strands were found in the resin cones.

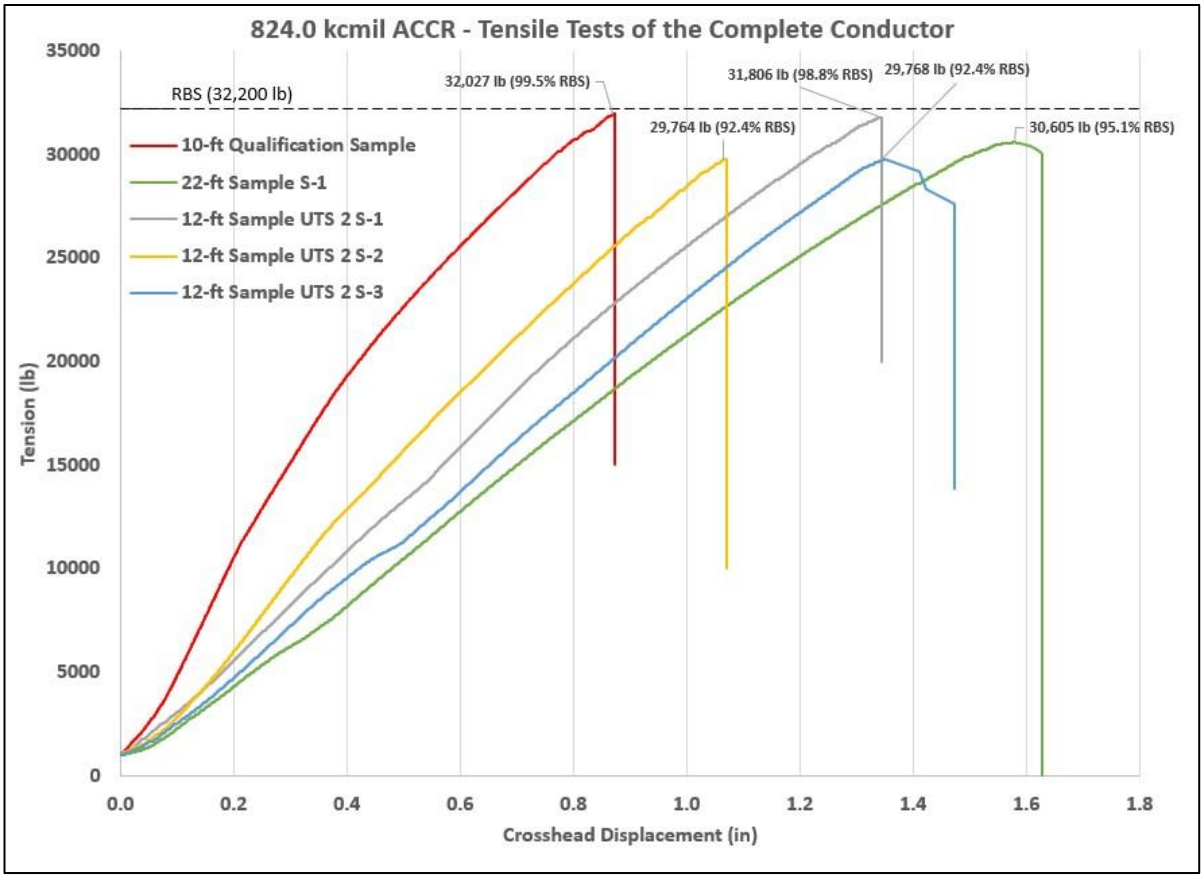

Figure 10: Complete Conductor Tensile Test Results

5.0 CONCLUSIONS

This report covers tensile tests from four (4) complementary approaches:

1. Individual core strands: two (2) of nine (9) strands tested failed below the ASTM B976 nominal requirement. Both were jaw breaks and results can be discarded. Overall results of the core strand tests are considered acceptable.

2. Individual aluminum alloy strands: area measurements were confirmed by three diverse methods and by two technicians performing the measurements independently. The measurements show the aluminum strand area and the total conducting area are 4% below the nominal requirement, and 2% below the minimum allowable requirement. Of nine samples tested, all exceed the 23,000 psi requirement if the <u>measured</u> strand area is used to compute the normalized strength. Two (2) of nine (9) strands failed below the nominal requirement if the 4% larger <u>nominal</u> area is used to compute the normalized strength. All of the aluminum alloy strands comfortably exceed the minimum required elongation.

   Nominal strand size requirements are important for conductor strength, line energy loss, and compatibility with fittings and connectors.

3. Complete 19-strand core: the single core test met the nominal strength requirement.

4. Complete 26/19 conductor: for the five (5) samples tested, the breaking loads ranged from 92.4% RBS to 99.5% RBS. Considerable effort was expended to ensure strength measurements were representative of the conductor section sent by WAPA. Failure location was not a major factor as some of the lower values were gage section breaks. Two resin cones were sectioned to observe strand placement and check for any slipped strands. No slipped strands were found.

   The individual strand data accounts for some of the performance shortfall. The rated strength is based on the nominal area of the aluminum strands, whereas the actual aluminum area is 4% lower. The aluminum strands account for 42% on the nominal RBS. A 4% shortfall in the aluminum area accounts for a 2% reduction in the breaking strength.

Conductor strength exceeds the nominal rating when computed using individual strand data. This is an anomalous result compared to the results of the five (5) complete conductor tests. A possible explanation is that the average core strand strength is used, but two of the nine core strands tested below the nominal rating. The MMC core does not yield prior to break. If one or two strands fail before the rated strength is reached, the breaks may trigger a cascade of breaks of the remaining intact core strands.

6.0 EQUIPMENT

Tinius Olsen universal testing machine (UTM), calibration control # CQ 0013

MTS long bed tensile machine, calibration control # CQ 0195

Gram scale (for mass method), calibration control # CQ7819

Mitutoyo 0-1” micrometer, calibration control # CQ 7817

2-ft caliper micrometer (sample length for mass method), calibration control # CQ6733

7.0 REFERENCES

ASTM B941, Heat Resistant Aluminum-Zirconium Alloy Wire for Electrical Purposes

ASTM B976, Aluminum Matrix Composite (AMC) Core Wire for ACCR Conductors

ASTM B978, ACCR Overhead Conductor