

Table 3-17. Technical specifications of TS conductors

Conductor	Type	Core	Aluminum	Overall Diameter	Kcmil	Core Diameter	RBS (lbf)	Connectors
TS 2021	CFCC	Single carbon fiber encapsulated in aluminum core	Two layers of 32 fully annealed trapezoidal AL alloy strands	1.108 inch (28.15 mm)	1026.9	9.50 mm	50,655	AFL B13510

### Endurance Test

The following observations were made with regards to the Maximum Load Tests on the Endurance Test assemblies:

1. The tension assembly reached 54,252 lbf, corresponding to 107.1% of the conductor’s RBS, before failure.
2. The dummy assembly reached 55,556 lbf, corresponding to 109.7% of the conductor’s RBS, before failure.
3. Both failures occurred inside the dead-end connector with a ductile fracture of the aluminum strands/tube and the composite core pulling out.

All compression dead-ends were installed as per AFL’s instructions, including the use of high temperature inhibiting compound. All four (4) connectors showed good thermal stability throughout the five hundred (500) cycles with slight temperature increases overall (~5°C to 12°C). All measurements were corrected to 20°C for comparison. The two (2) compression dead-ends installed on the dummy assembly showed negligible changes in DC resistance readings, 0.0 μΩ and 0.2 μΩ, from cycle 0 to cycle 500. The two (2) compression dead-ends installed on the tension assembly showed increases of 2.5 μΩ and 1.4 μΩ from cycle 0 to cycle 500. This represents an increase of 11.0% and 6.2%, respectively, between the initial and final DC resistance readings of the tension assembly connectors.

The mouths of all dead-end connectors were marked to detect any slippage or conductor movement during the Endurance Test. No movement was observed on any connectors during the five hundred.

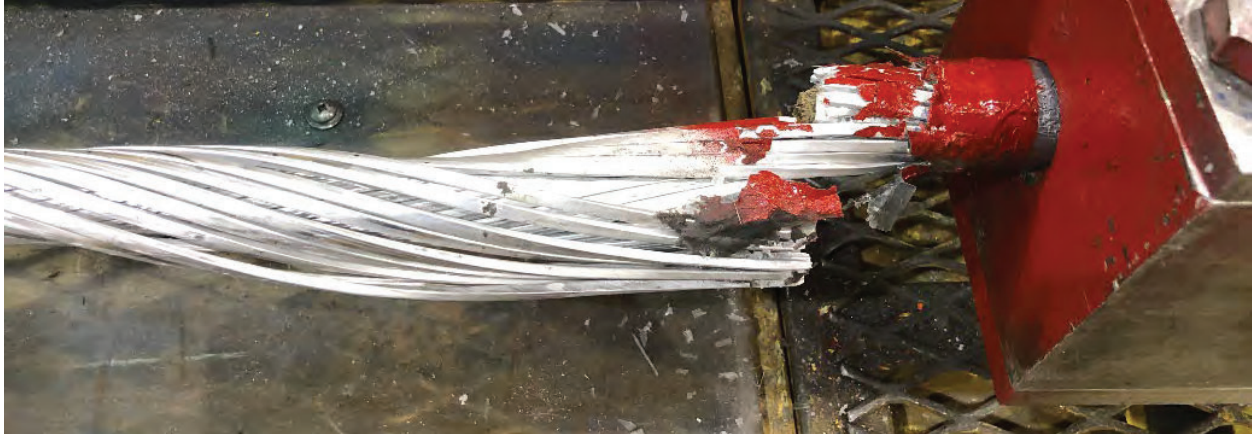


Figure 3-20. Typical Failure Appearance after Endurance Test (Tension Sample) on TS CFCC conductors

The Endurance Test was performed to demonstrate the performance of the TS Drake 150 9.5 TWD conductor when exposed to combined thermal and mechanical stresses. All steady-state temperature measurements taken along the TS CFCC conductor and connectors of the tension and dummy assemblies showed good overall thermal stability during the five hundred (500) thermo-mechanical cycles. No slippage or movement at the dead-end connectors was noticed during the five hundred (500) thermo-mechanical cycles and five (5) 70% RBS holds. Furthermore, the dead-end connectors showed good electrical performance and minimal changes in DC resistance. The tension and dummy assemblies reached 107.1% RBS (broken TS CFCC conductor shown in Figure 3-23) and 109.7% RBS before failure occurred. The results of the Endurance Test suggest that the combination of thermal and mechanical stresses do not cause a reduction in the mechanical strength of the TS Drake 150 9.5 TWD conductor connector assemblies as evaluated.

### Summary

Table 3-18. Summary of TS CFCC conductor’s performance

Composite	Test temperature	Endurance test	Breaking Load test (%RBS)
TS (2021)	160±5 degC	Pass	Pass (UTS equal to 107.1%)

## Summary/Comparison/Conclusion

### Endurance Tests

The rated breaking strength (RBS) of various conductors are illustrated in Figure 3-24. The RBS of glass and carbon fiber-based conductors were in general higher in comparison to the conductors with polymer matrix carbon fiber composites. The RBS of CTC conductors increased to 46,600lbf in case of CTC/Lamifil conductors primarily due to the increased carbon fiber content in comparison to 41,000lbf in case of CTC/GC conductors.

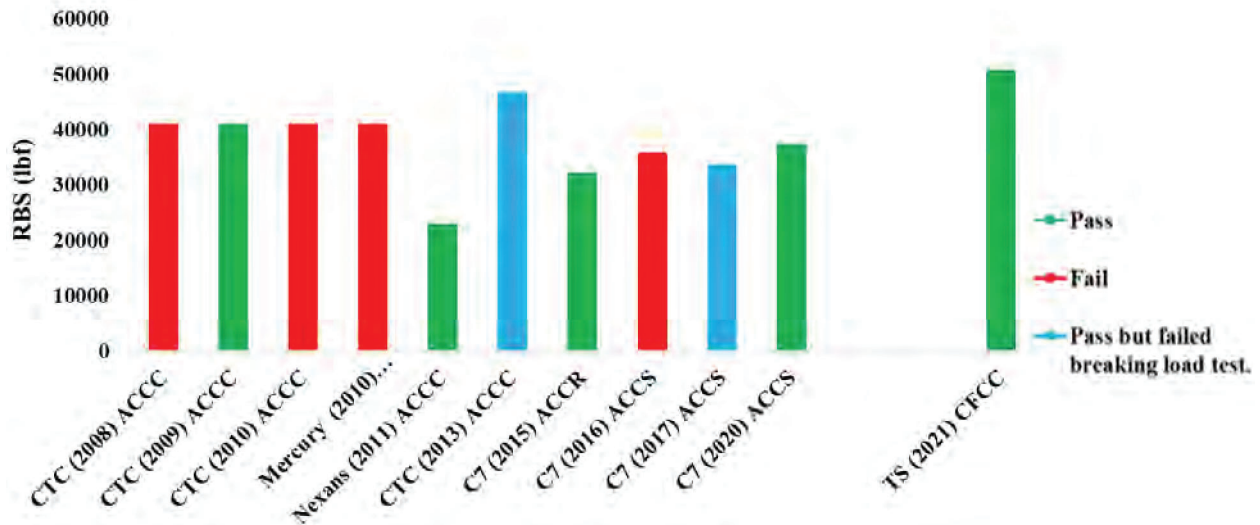


Figure 3-21. Comparison of RBS values of various conductors

In case of C<sup>7</sup> conductors with core manufactured by Celanese corporation, strangely, the ACCR conductors were rated at a lower RBS (32,100lbf) in comparison to ACCS conductors. The ACCS conductor was down rated (passed the test for 33,500RBS) after failing the qualification test with a higher RBS (35,800lbf). But in case of C<sup>7</sup> conductors with core manufactured by Tokyo rope international, the RBS was higher (37,200lbf) in comparison to the previous ones probably due to the presence of carbon fiber composite core.

In case of Nexans Lo-sag conductors, the RBS was estimated to 22,930lbf although the geometry and conductor composition was like CTC ACCC conductors except the smaller core diameter (7.7mm as against 9.53mm). Mercury cable conductors similar in geometry to CTC conductors were rated the same. However, they failed the qualification test due to slippage of the conductor out of the dead-end joint (mechanical failure).

Of all the conductors evaluated, TS conductors (formerly WTEC) had the highest RBS (50,655lbf) due to the combination of having both carbon fiber composite core (CFCC) and stronger Al alloy in the conductor composition.

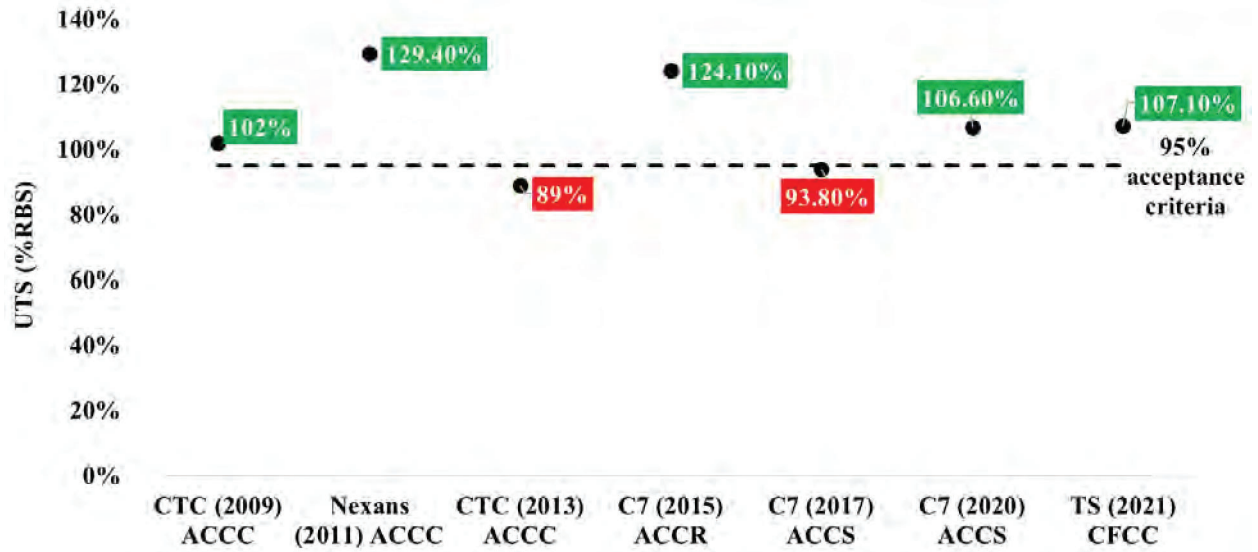


Figure 3-22. Breaking strength of conductors after breaking load test

Figure 3-25 represents the breaking strengths of conductors that passed the qualification test during the breaking load test. Although the conductors manufactured by CTC/Lamifil, Celanese/Southwire (2017) passed the thermo-mechanical test without noticeable failure, their strength deteriorated after the test (breaking strength measured during the breaking load test was 89%RBS and 93.8%RBS respectively) which can be indication of slight over estimation of RBS for them. The estimation of RBS for CTC/GC, Tokyo rope/Southwire and TS conductors were found to be reasonable since no deterioration of mechanical properties were found after the aging test.

Table 3-19. Overall results of the conductors analyzed

Composite	Test temperature	Endurance test	Breaking Load test UTS (%RBS)	T <sub>g</sub> test	Bending test
CTC global/GC (2008)	190±1°C	Fail (Core failed at 400 cycles due to localized heating)	N/A	Fail (Difference in final and initial T <sub>g</sub> ~ -30°C)	N/A
CTC global/GC (2009)	180±1°C	Pass	102		N/A
CTC global/GC (2010)	200±2.5°C	Fail (Core failed at 400 cycles since core could not withstand 200°C)	N/A		Fail
Mercury cable (2010)	180±5°C	Fail (Core failed at 100 cycles. Mechanical failure of the dead-end joint)	N/A	Pass (Difference in final and initial T <sub>g</sub> ~ ~12°C)	Pass
Nexans (2011)		Pass	129.4	Pass (Difference in final and initial T <sub>g</sub> ~ ~1°C)	Pass
CTC/Lamifil (2013)		Pass	Fail (89% RBS since the conductor was rated at a higher RBS)	N/A	N/A
Celanese/Southwire (2015)		Pass	124.1	No T <sub>g</sub> test	N/A
Celanese/Southwire (2016)		Fail (Core failed after 300 cycles by pull-out-insufficient radial gripping strength of the connector on the core)	N/A		N/A
Celanese/Southwire (2017)		Pass	93.8		N/A
Tokyorope/Southwire (2020)		Pass	106.6		N/A
TS (2021)		160±5 °C	Pass		107.1

## Tg Tests

The  $T_g$  values of conductors were measured before and after the aging tests. The values of Mercury cables and Nexans conductors either didn't change or increased hence proving that there is a good chance that the conductor would be stable, and the maximum operating temperature is accurate for these conductors. However, CTC didn't fare well in this case and the value were lowered by 30°C after aging tests hence deeming a reconsideration of the maximum operating temperature necessary.

Table 3-20. Compilation of Tg tests of various conductors

	CTC	Mercury cable	Nexans
$T_g(\text{final})-T_g(\text{initial})$	-30 °C	+12°C	-1°C
<b>Result</b>	Fail	Pass	Pass

## Bending Mechanical Tests

The mechanical properties of Nexans and Mercury cable conductors (taking the experimental tolerance into consideration) indicated that there was no change in the properties of the conductor. However, the mechanical properties of CTC conductors after aging test were not measured since the conductors was too damaged to perform any kind of analysis.

Table 3-21. Results of bending mechanical tests

Composite		Max $\alpha$ (MPa)	Max Deflection (mm)	E (GPa)
CTC	Initial	547.4	1.7	37.9
	Final	Samples were not recoverable for final mechanical testing		
Nexans	Initial	731.8	1.792	53.78
	Final	852.6	2.0925	53.67
Mercury Cable	Initial	624.08	1.90	46.90
	Final	618.27	1.87	47.87

## Conclusion

This study on advanced conductors is intended towards comparison of their performance during the thermo-mechanical tests against manufacturer's specifications. Also, this report is a compilation of the evaluation of various advanced conductors studied over the past 14 years at EPRI. The performance of these conductors during the thermo-mechanical tests conducted is an indication of their real-world performance and should be considered during the electrical transmission design process. Most of the advanced conductors perform within the range specified by the manufacturer and the appropriate ASTM standards. It can be safely said that the manufacturer's specifications can be taken as guideline for the performance of these conductors in most cases.

The following observations were made on the conductors studied:

The maximum operating temperature of all the conductors studied shall not exceed 180°C.

Conductors with carbon fiber core performed better (higher mechanical strength) in comparison to conductors with glass/composite core.

Aluminum encapsulation around the core and extra annealed aluminum outer strands in comparison to other conductors combined with testing temperature slightly lower (160°C) than other conductors might probably be the reasons for the TS (WTEC) conductor's enhanced mechanical strength.

Nexans lo-sag conductors were probably rated at a lower strength and hence performed exceedingly in the mechanical tests with breaking load exceeding tensile strength by 30%.

The glass transition temperature ( $T_g$ ) of CTC conductors was lowered after aging tests however, it either remained the same or slightly increased for Mercury cable and Nexans conductors indicating that the CTC have lower, and others have higher thermal stability in comparison. This is also shown in the bending mechanical properties of the CTC conductors being lower after thermal aging in contrast to other conductors studied.

These studies suggest that most of the manufacturers have specified specifications closer to the expected properties or have been receptive to unsuccessful tests by tweaking the specifications to conform to industry standards.