Electromechanical Performance of CORC® Cables and Wires under Axial Tension and Transverse Compression

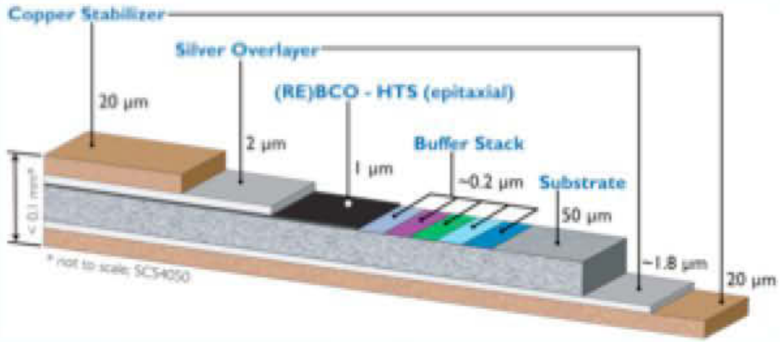
Danko van der Laan & Jeremy Weiss
Advanced Conductor Technologies & University of Colorado, Boulder, Colorado, USA

Supported by U.S. Department of Energy contracts DE-SC0007660, DE-SC0014009, DE-SC0015775 and DE-SC0018125

Advanced Conductor Technologies
www.advancedconductor.com

MT26, September 26th, 2019, Vancouver, Canada

CORC® magnet cables and wires



RE-$Ba_2Cu_3O_{7-\delta}$ coated conductor made by SuperPower Inc.

Single tape wound into a CORC® cable

CORC® wires (2.5-4.5 mm diameter)

- Wound from 2-3 mm wide tapes with 30 μm substrate
- Typically no more than 30 tapes
- Highly flexible with bending down to < 50 mm diameter

CORC® cable (5-8 mm diameter)

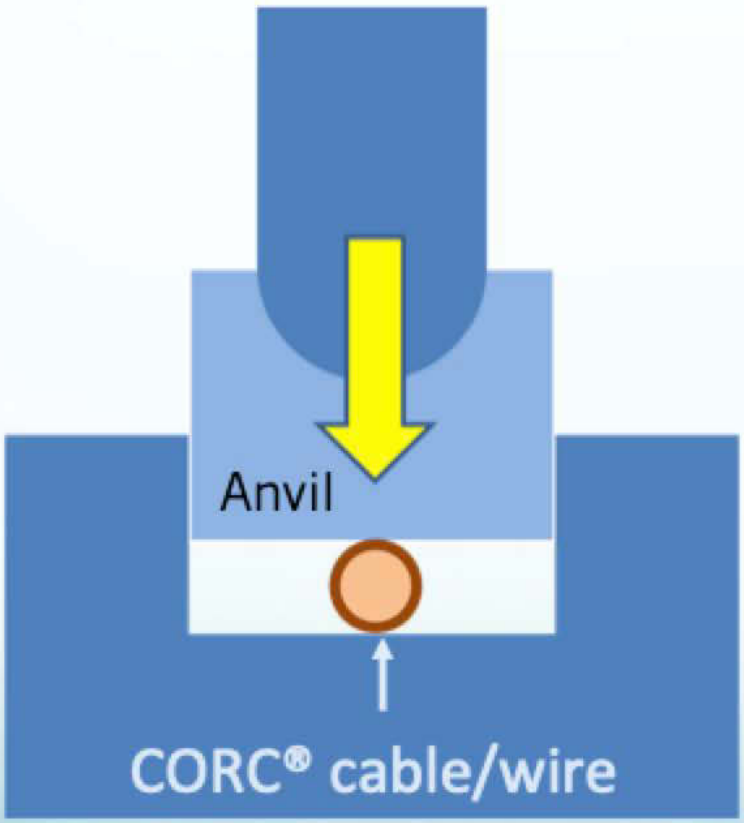
- Wound from 3-4 mm wide tapes with 30-50 μm substrate
- Typically no more than 50 tapes
- Flexible with bending down to > 100 mm diameter

Advanced Conductor Technologies
www.advancedconductor.com

Application of transverse compressive load

Measurement under transverse compressive load

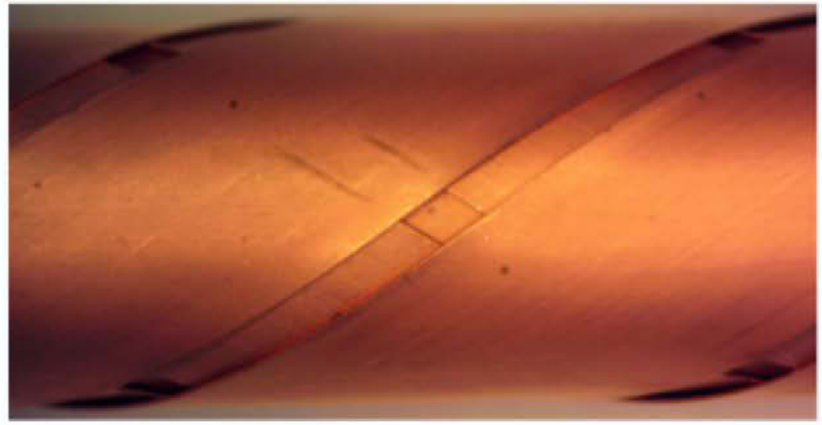
- Load applied by two flat stainless steel anvils
- Load applied at 76 K in liquid nitrogen



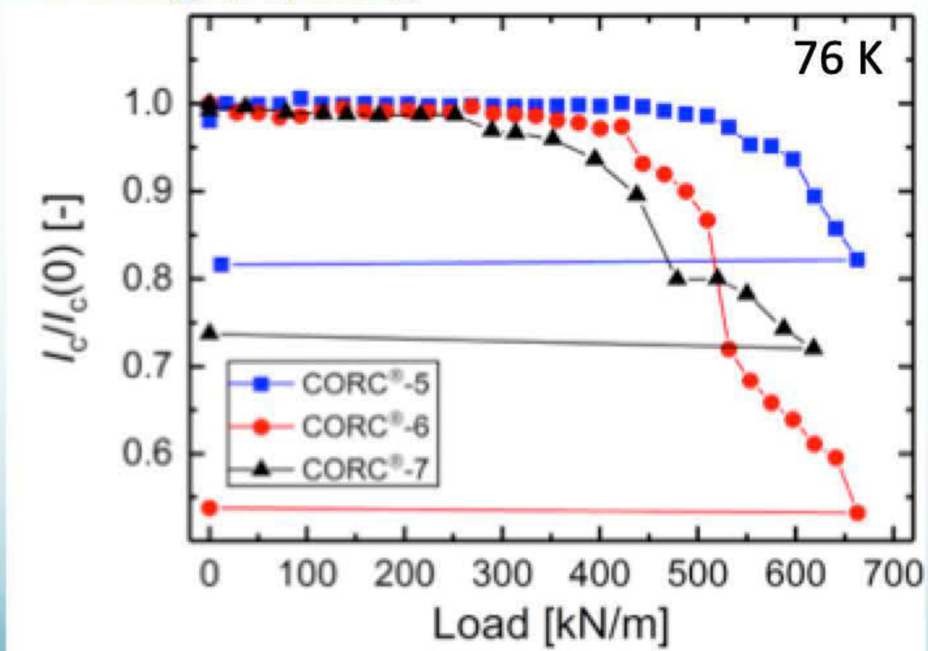
CORC® cables: Effect of tape gap spacing

Model CORC® sample

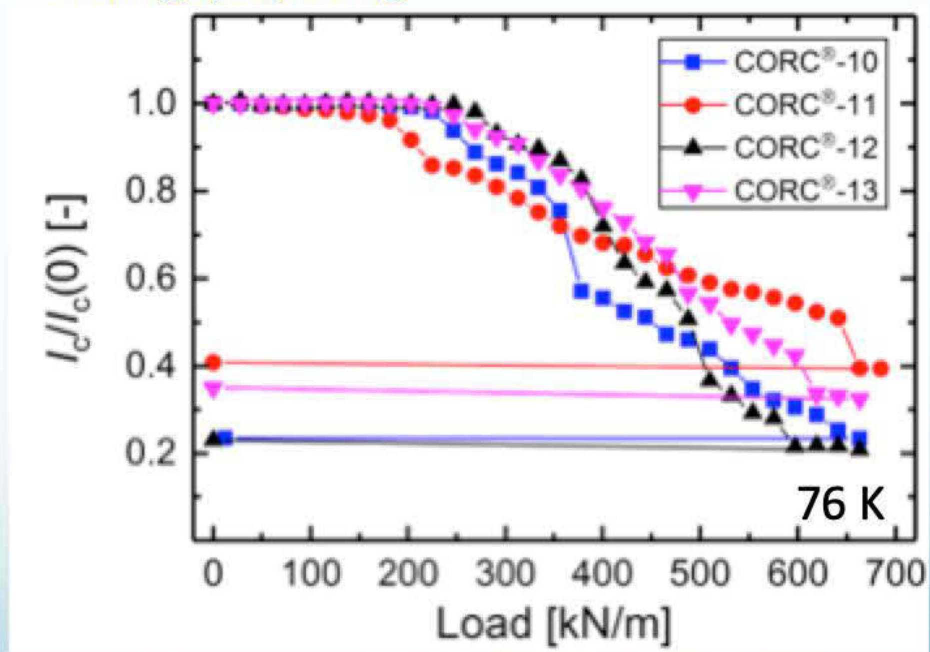
- Hand-wound
- **Solid stainless steel former**
- 3 layers, 6 or 9 tapes
- Gap spacing 0 or 1 mm
- Copper plating 5 μm thick



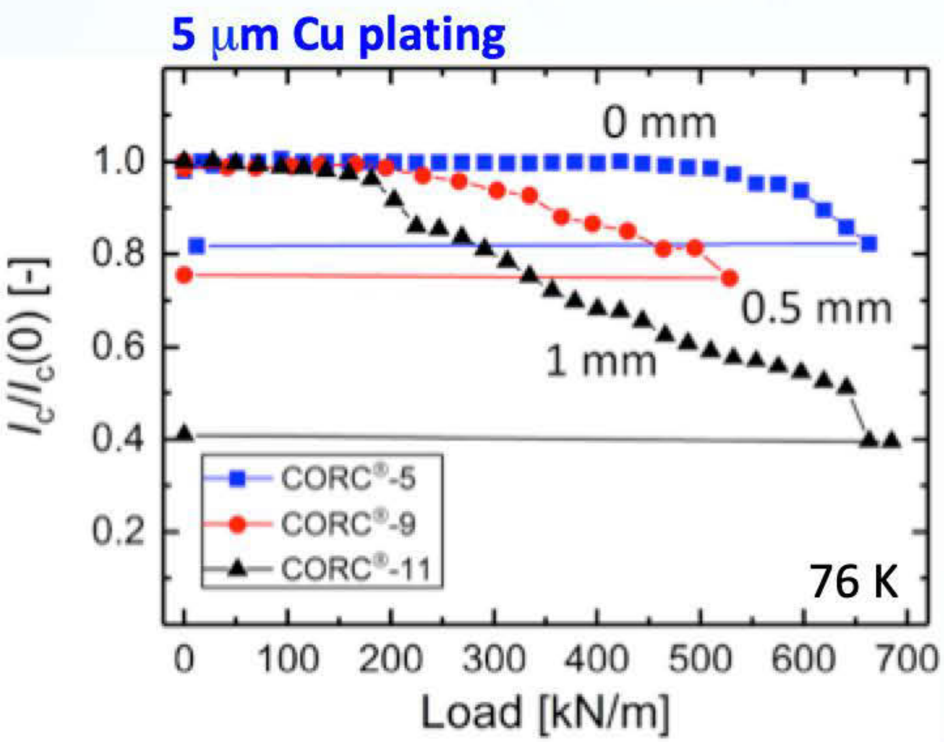
0 mm gap spacing

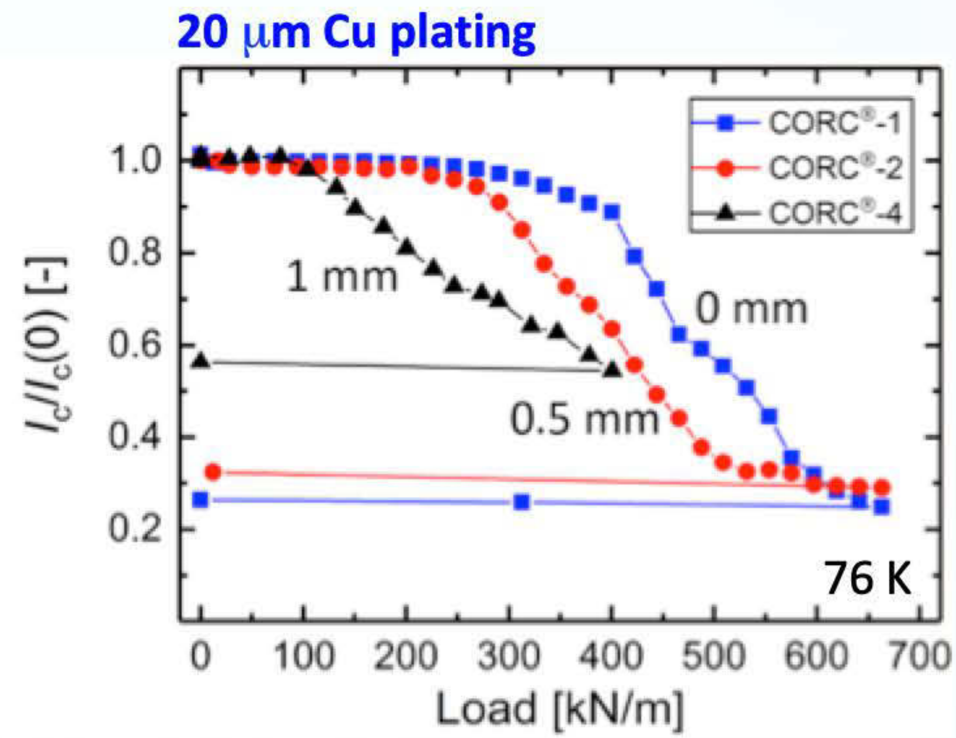


1 mm gap spacing



CORC® cables: Effect of copper plating thickness





Critical load decreases with copper plating thickness

Critical load decreases with gap spacing

Critical load [kN/m]

	20 μm copper plating Gap spacing:			5 μm copper plating Gap spacing:		
I_c decrease	**0 mm**	**0.5 mm**	**1.0 mm**	**0 mm**	**0.5 mm**	**1.0 mm**
1%	250	200	150	360	210	200
3%	260	200	160	420	250	230
5%	270	220	180	450	290	240

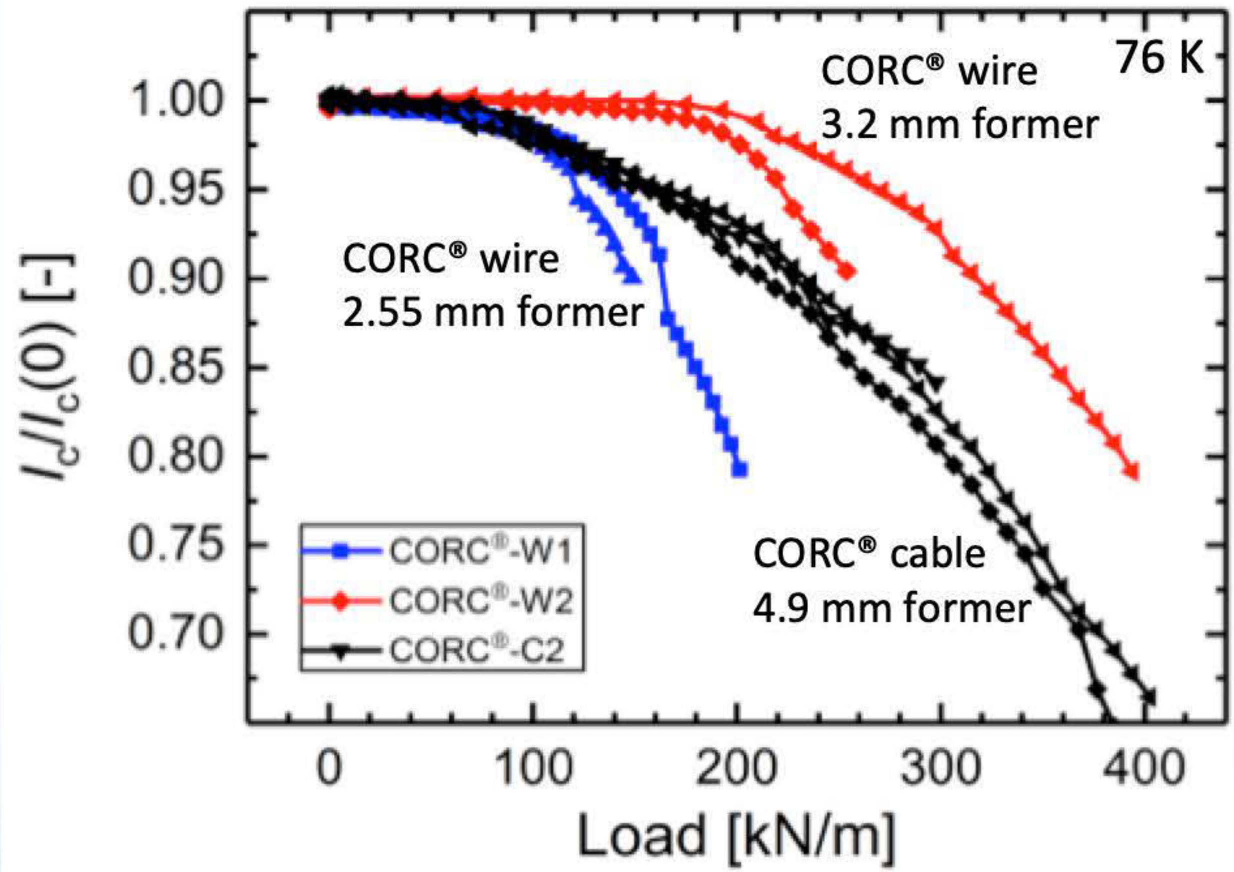
Transverse compression on CORC® cables and wires

CORC® cable and wire layout

- Machine-wound
- Tapes with 5 μm copper
- 0.3 – 0.4 mm gap spacing

Critical load [kN/m]

I_c decrease	CORC®-C1	CORC®-C2	CORC®-W1	CORC®-W2
3%	207	124	115	217
5%	255	160	133	243
10%	340	226	163	284

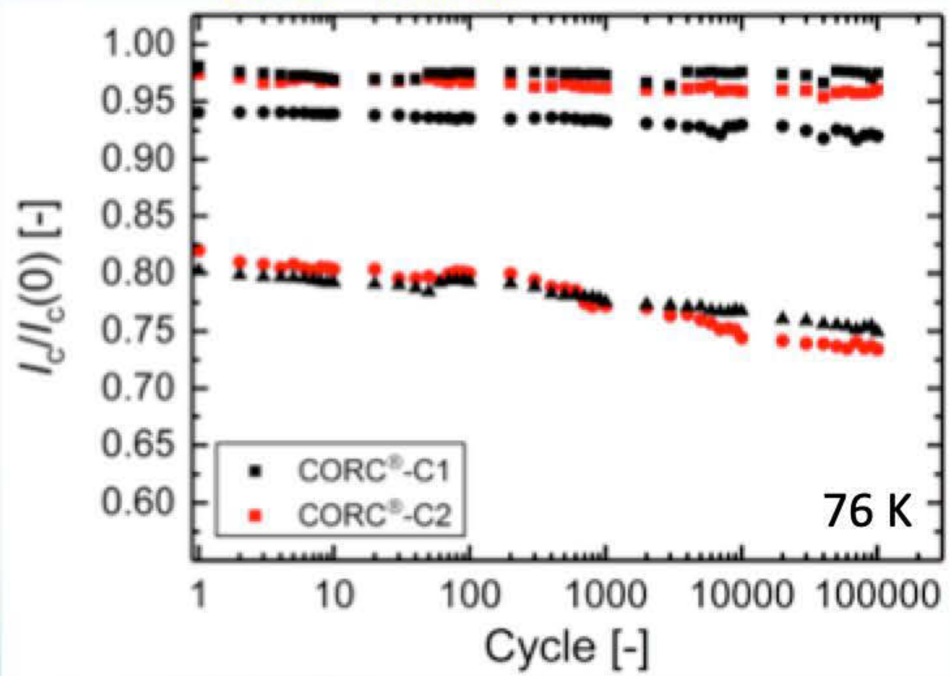


Effect of transverse compressive load cycling

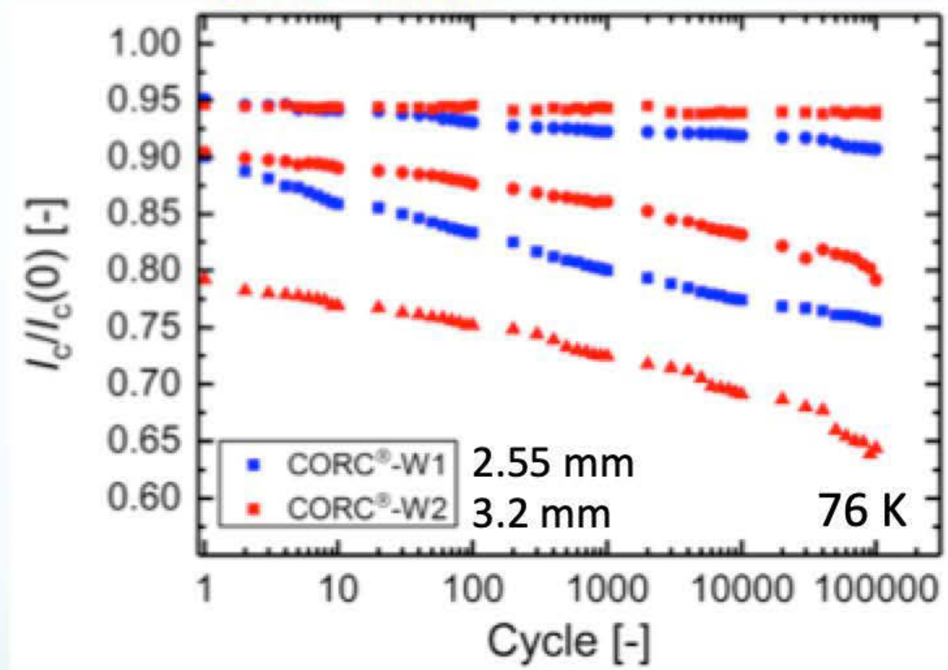
Test procedure for cycling in liquid nitrogen

- Each sample is loaded to peak load responding to predetermined I_c retention: 95 – 97 %, 90 %, and 80 %
- Load cycled between 10 % and 100 % of peak load

CORC® cables



CORC® wires



Peak load with I_c retention > 95 %: No significant additional I_c degradation after 100k cycles
Peak load with I_c retention < 90 %: Additional I_c degradation after 100k cycles < 5 – 10 %

Advanced Conductor Technologies
www.advancedconductor.com

Axial tensile stress setup

Testing CORC® wires with copper former

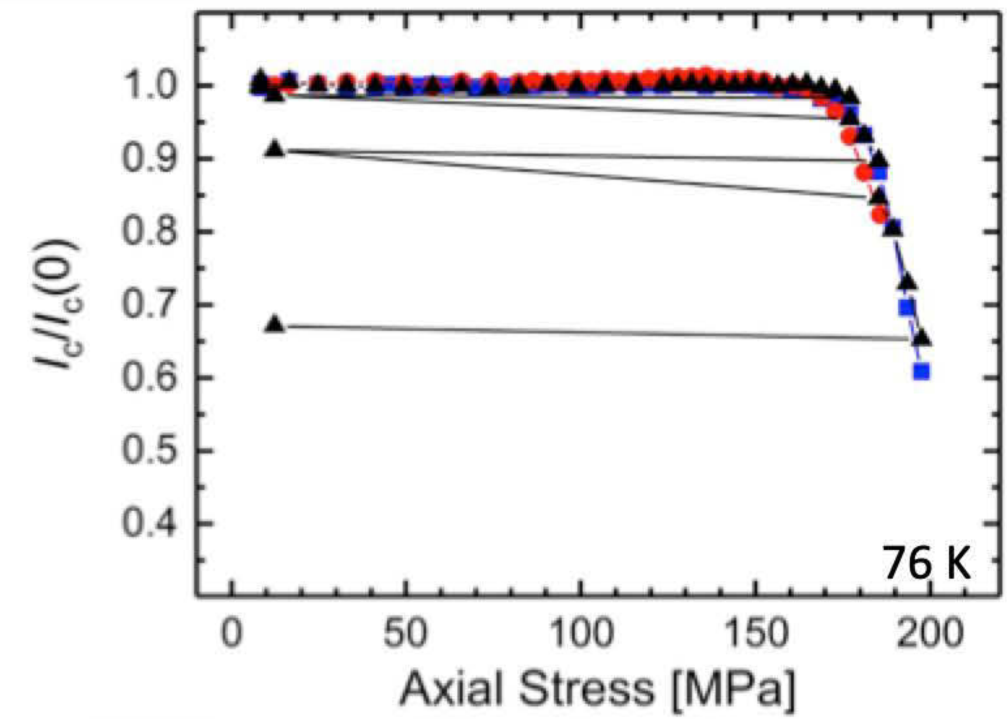
- Test machine capacity = 13 kN
- Load applied through current injection terminals
- Monotonic and cyclic stress applied in liquid nitrogen

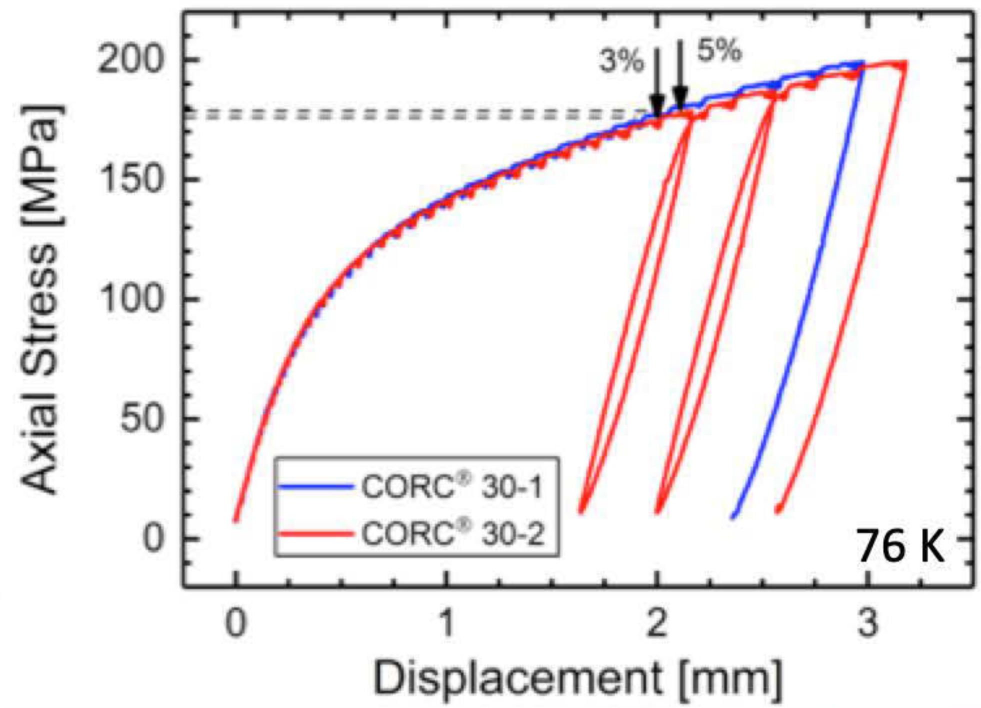
Advanced Conductor Technologies
www.advancedconductor.com

Monotonic axial tensile stress test results

Sample details

- CORC® wire with 30 tapes
- Solid annealed copper former of 2.55 mm diameter



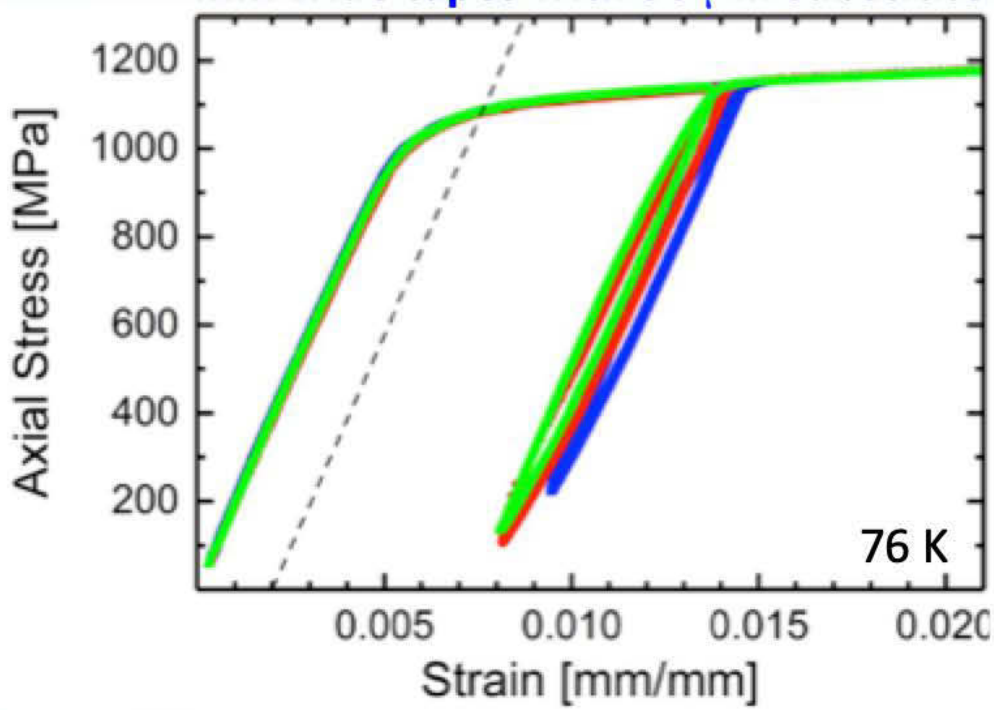


No reversible I_c reduction before irreversible stress limit of 177 MPa
CORC® wire has yielded significantly before I_c degradation occurred

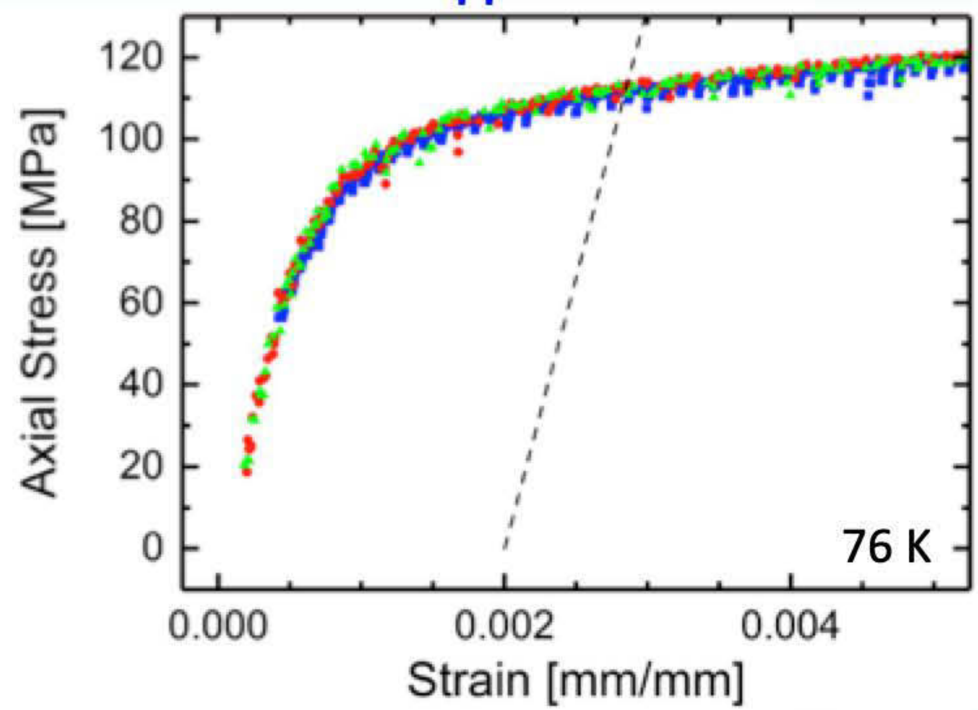
Advanced Conductor Technologies
www.advancedconductor.com

Stress-strain of CORC® wire former and tapes

2 mm wide tapes with 30 μm substrate



2.55 mm copper former



Yield stress (76 K, 0.2 % strain)

- **Tapes: 1,092.7 MPa**
- **Former: 109.7 MPa**

Advanced Conductor Technologies
www.advancedconductor.com

Comparing stress-strain curves of CORC® wires

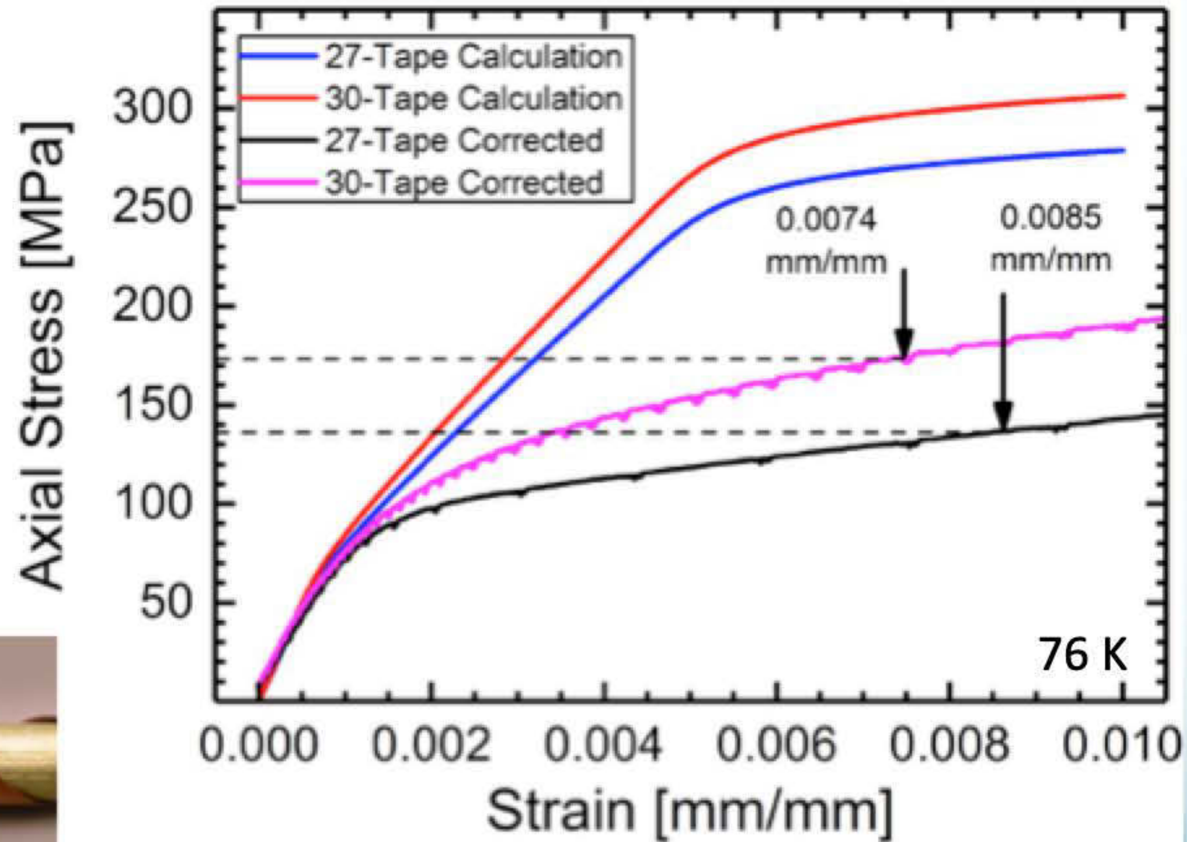
Stress-strain dependence calculated with rule of mixtures (ROM)

- 27 or 30 tapes with Yield stress 1,092.7 MPa
- 2.55 mm thick former with Yield stress of 109.7 MPa

Large difference in CORC® wire Yield stress (0.2 %)

- ROM: 250 – 270 MPa
- Actual samples: 100 – 120 MPa

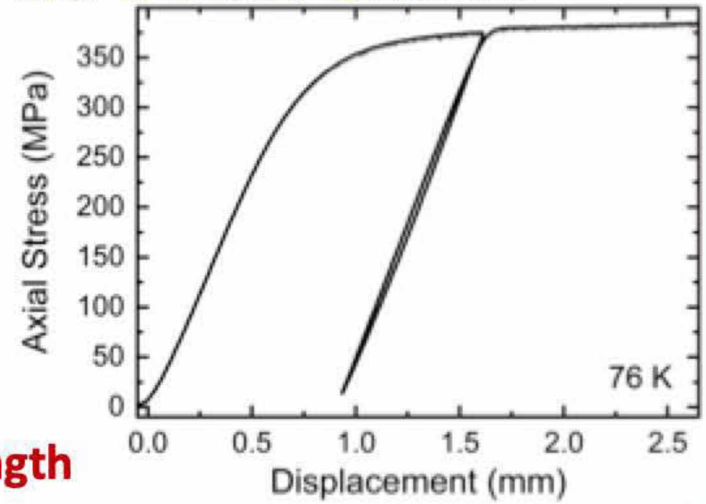
Difference explained by ROM assumes straight parallel tapes, while tapes in CORC® wire are springs



Advanced Conductor Technologies
www.advancedconductor.com

CORC® wires with hardened former

2.57 mm hard Cu former



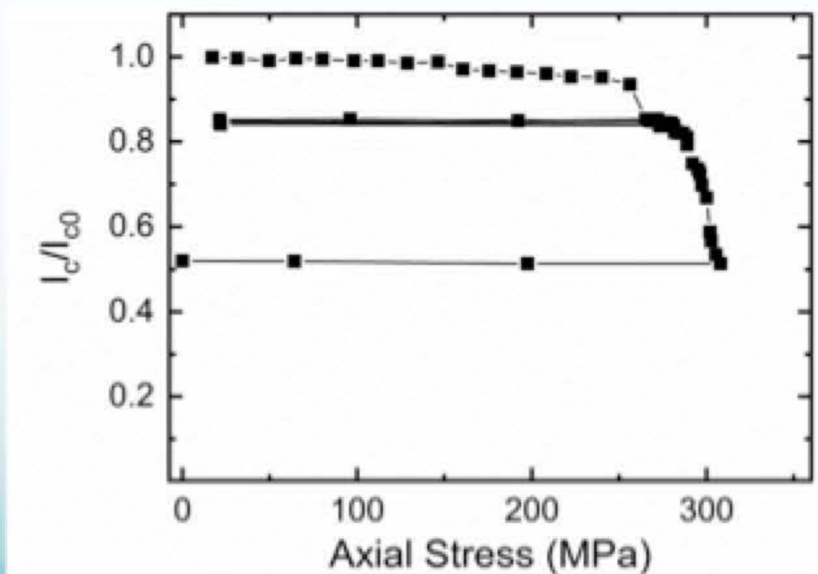
Sample details

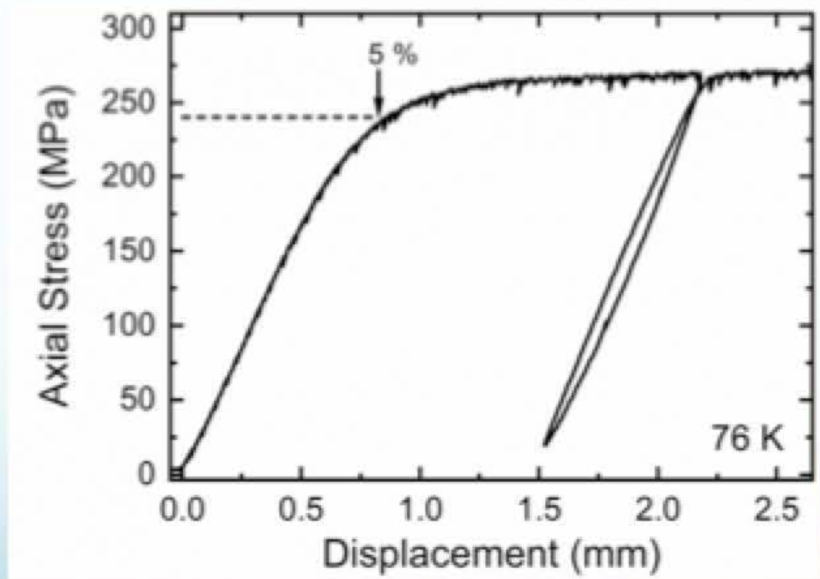
- 16 tapes with Yield stress 1,092.7 MPa
- 2.57 mm thick hard Cu former: Yield stress 350 MPa

CORC® wire performance

- Initial drop in I_c at 265 MPa likely due to terminations
- Critical stress (5 % I_c degradation) 245 MPa
- Typical rapid decrease in I_c at 280 MPa

Stronger former results in increase on CORC® wire strength





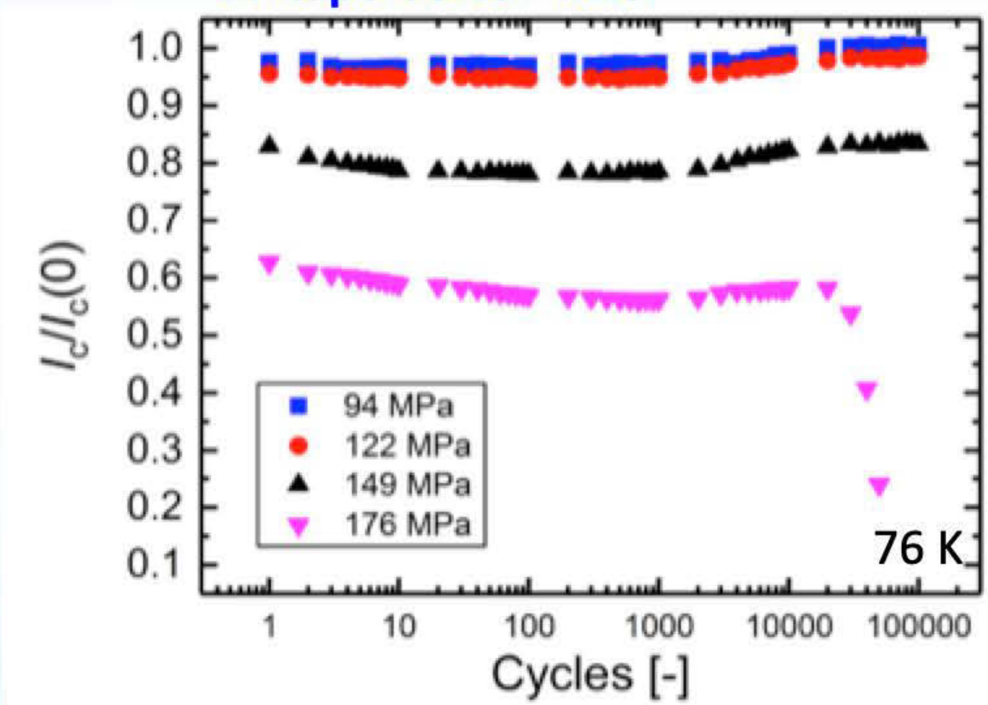
Advanced Conductor Technologies
www.advancedconductor.com

Axial tensile stress fatigue of CORC® wires

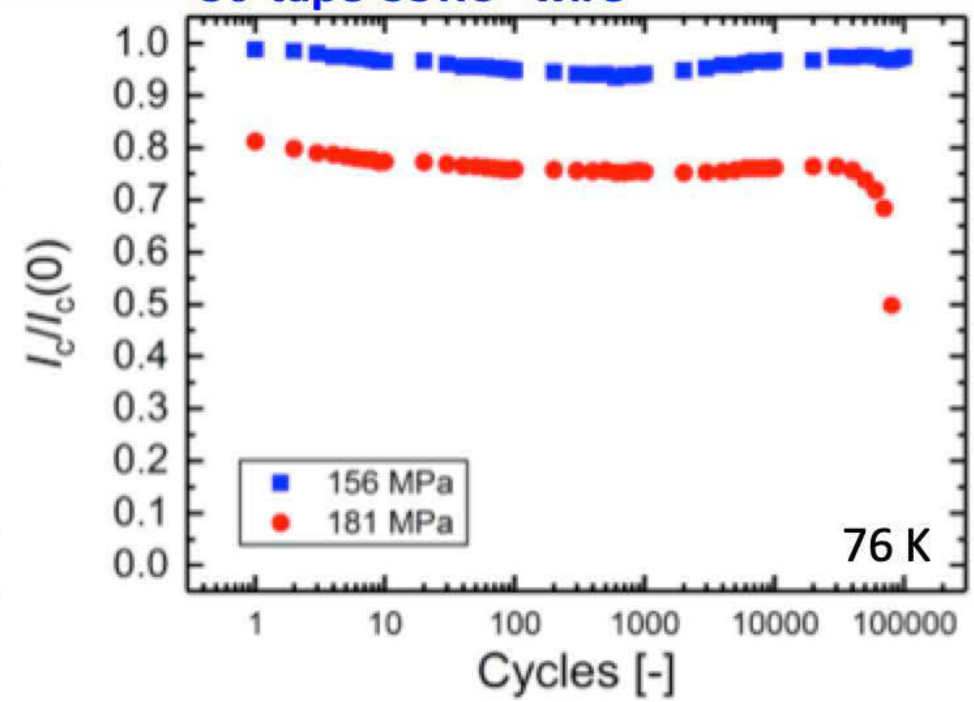
Test procedure for cycling in liquid nitrogen

- Each sample is loaded to peak load responding to predetermined I_c retention: 95 – 97 %, 80 %, and 60 %
- Load cycled between 10 % and 100 % of peak load

27-tape CORC® wire



30-tape CORC® wire



Source of the change in I_c (decrease followed by recovery) during cycling unknown
Once real degradation occurs at stress exceeding the irreversible stress limit, I_c falls off a cliff

Advanced Conductor Technologies
www.advancedconductor.com

Summary

Effect of transverse compressive load on CORC® cables and wires

- Larger gaps spacing between tapes and thicker copper plating on tapes decrease irreversible load limit
- Irreversible transverse compressive load limit of practical CORC® cables and wires depends on strain state of their tapes after winding
- Cyclic loading to 100,000 cycles doesn't cause significant additional degradation at peak stress where retention of I_c is > 90 %

D.C. van der Laan, D.M. McRae and J.D. Weiss, SUST 32, 015002 (2019)

Effect of axial tensile stress on CORC® wires

- Critical stress of 30-tape CORC® wire with annealed copper former > 177 Mpa
- Critical stress increased to > 245 MPa by using harder temper copper former
- I_c degradation occurs when CORC® wire has yielded significantly
- Stress cyclic to 100,000 cycles only affects I_c when peak stress much higher than irreversible stress limit
- Significant difference in failure mode between transverse compression and axial tension

D.C. van der Laan, D.M. McRae and J.D. Weiss, SUST 32, 054004 (2019)