# Carbon Nanotube Low Voltage Differential Signal Cables for Space Applications

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EVERY CONNECTION COUNTS

TE connectivity

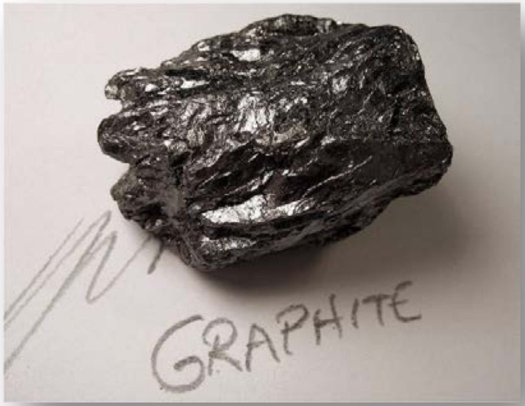
# Agenda

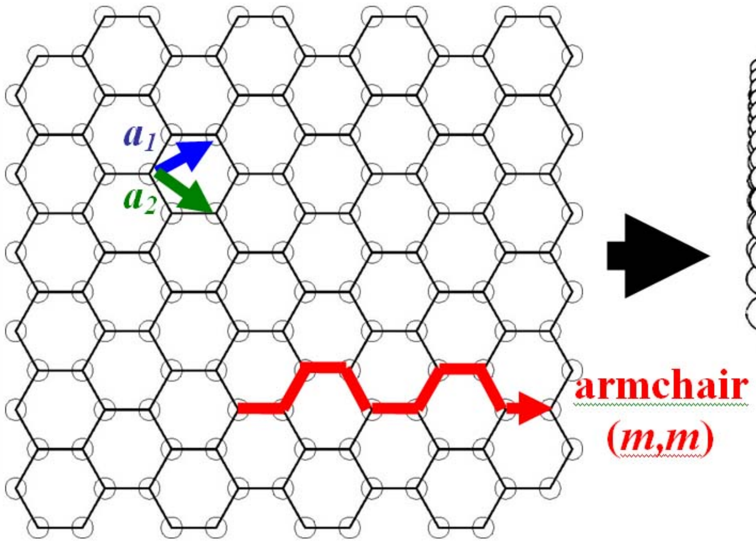
- CNT Introduction
- CNT for Wire and Cable
- CNT Characterization
- CNT Prototype Line
- CNT Termination
- Preliminary Electrical Characterization
- Conductivity Comments
- Summary
- Questions & Answers

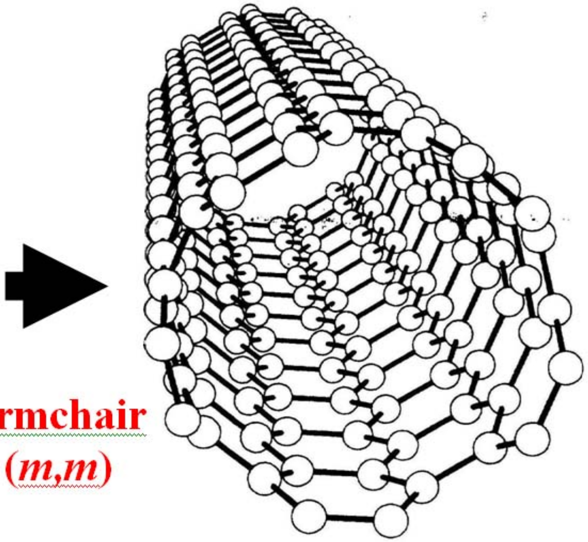
# CNTs: A Brief Introduction

# Carbon Nanotubes - Visualization

*Roll up a single atomic layer of graphite*



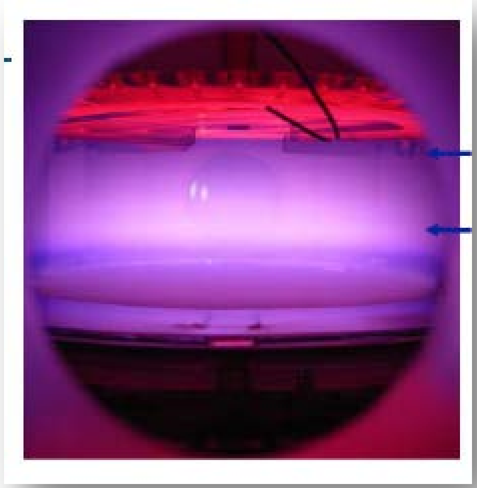
Graphite → Graphene → Carbon Nanotube

**CNTs identified in 1991 by Iijima**

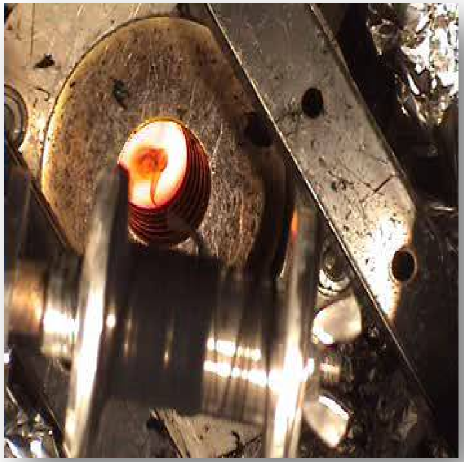
# CNT Manufacturing Methods

CNTs are manufactured by high temperature processes

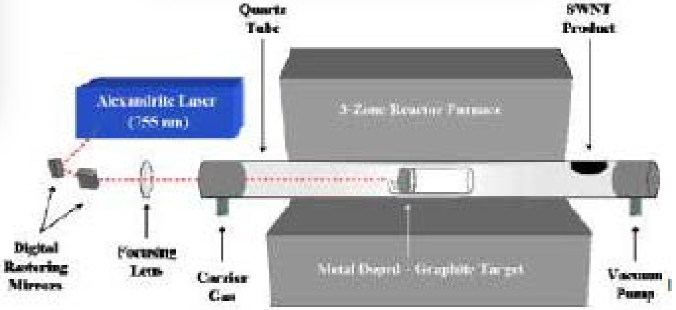
Plasma Enhanced CVD



Thermal Reactor

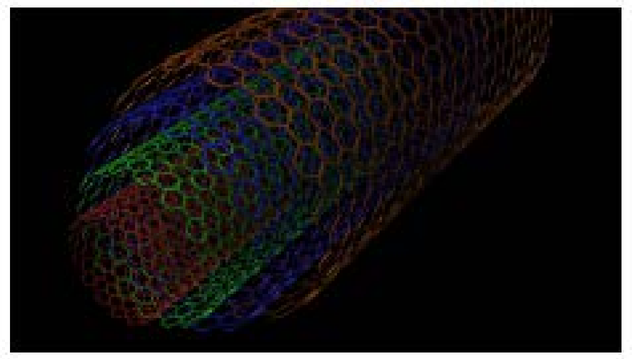


Laser Ablation



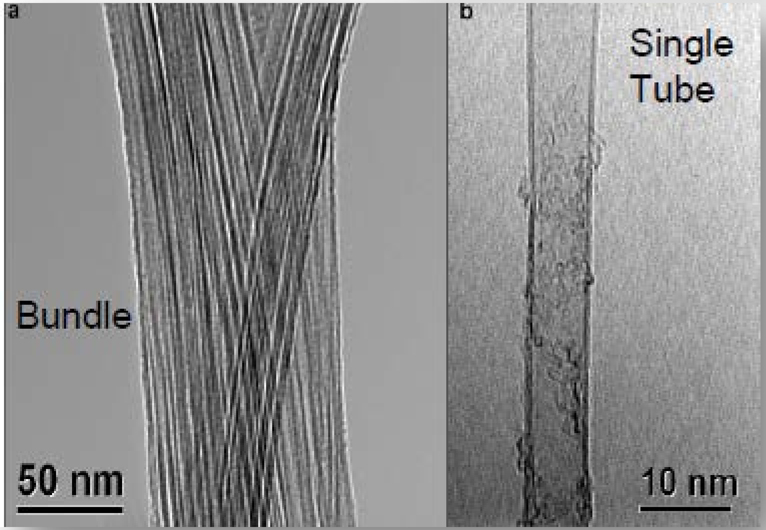
# CNT Manufacturing Methods (2 of 2)

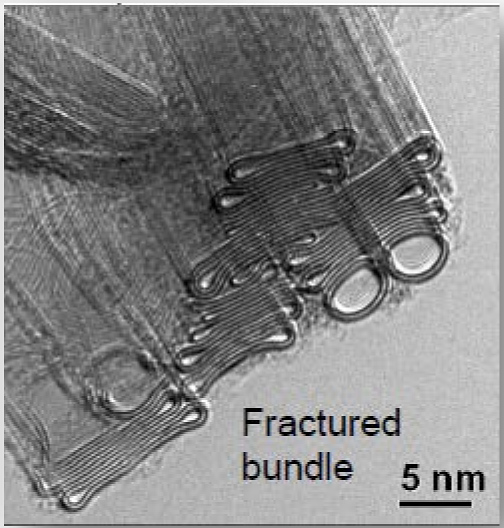
Temperature, catalyst, and reactor chemistry alter the CNT physical structure and conductivity



Physical Structure
- Single walled
- Dual/Few Walled
- Multi-Walled

Conductivity
- Metallic
- Semiconducting



# Aspect Ratio Creates Unique Properties

- CNTs are few nanometers in diameter and up to mms in length; this aspect ratio creates unique material properties

- For comparison, imagine re-bar 1cm in diameter and 1km in length

| | CNT | Steel | PbO | Al |
|---|---|---|---|---|
| Young's Modulus (TPa) | .8 – 1.4 | 0.3 | .36 | .07 |
| Tensile Strength (GPa) | 63 | 2 | 5.7 | 0.3 |
| Density ($g/cm^3$) | 1.4 | 8 | 1.6 | 2.7 |
| | CNT | Cu | Ag | Al |
| Electrical Resistivity (µΩ cm) | 1 | 1.7 | 1.55 | 2.7 |
| | CNT | Diamond | | |
| Thermal Conductivity (W mK) | 3000 | 2000 | | |

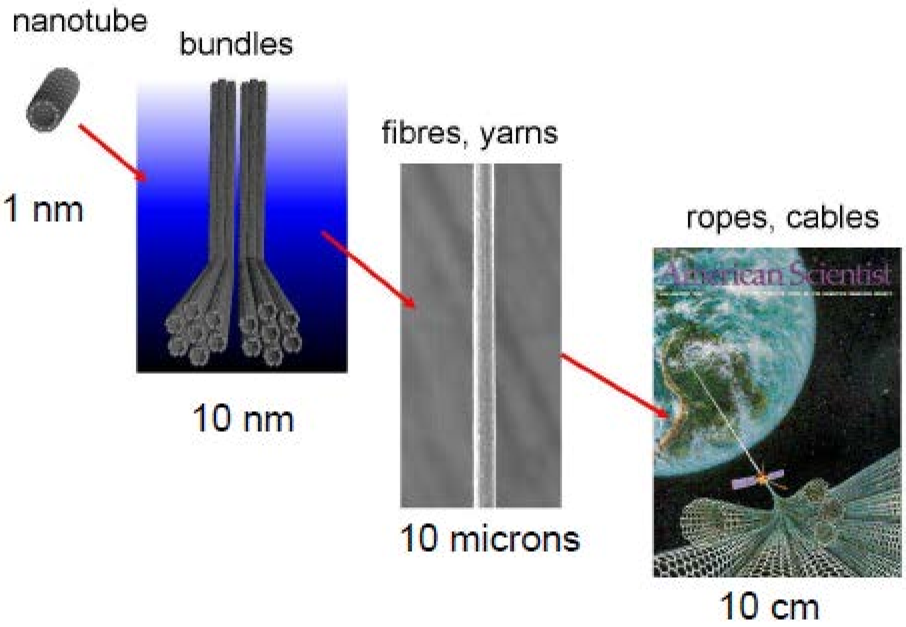
- Single CNTs are strong with high thermal and electrical conductivity

- As a non-metallic “conductor” CNTs are also corrosion and fatigue resistant.

# What's the Catch?

- Single CNT material properties **outperform** steel in strength, copper in electrical conductivity & diamond in thermal conductivity

- Properties **degrade** in assemblies of CNT



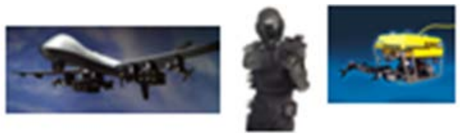

**Challenge:**
**How to maintain properties while changing scale 8 orders of magnitude**

# CNT for Wire and Cable

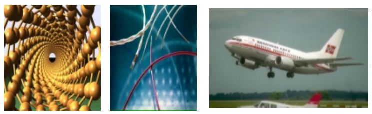
# Market Drivers: Size Weight and Power (SWaP)

Traditional SWaP

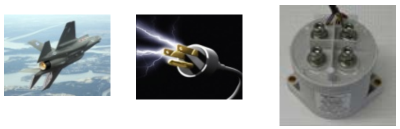
**Smaller Size**



**Reduced Weight**

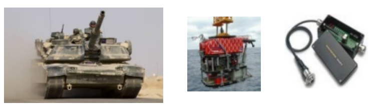


**More Power**

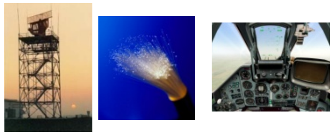


Customer Needs

**More Reliability**



**More Bandwidth**



Unstated Driver

*A customer suggested the acronym should be "**$WaP**"*

# CNTs and SWaP

✓Size
- Mechanical strength and fatigue resistance allow down-gauging
- Flexibility equivalent to textile threads

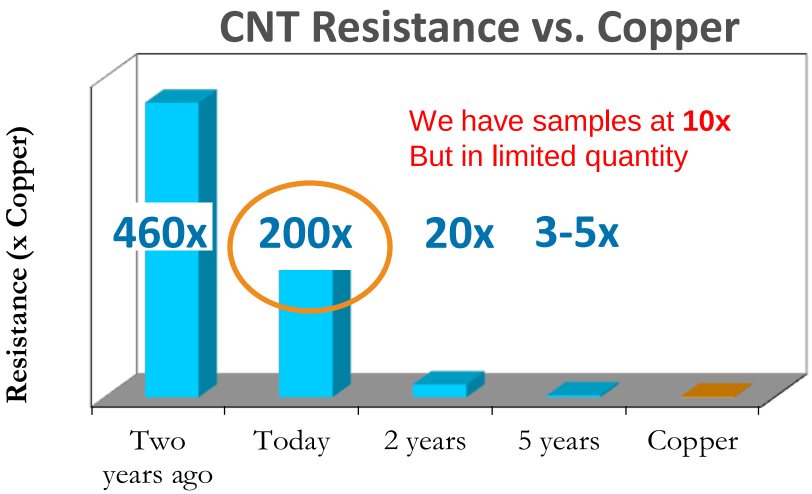
✓ Weight
- 30% to 70% savings based on cable construction

✓ Reliability
- Flex bend test cycles exceed 1.5M
- Corrosion and flame resistant (stable above 300C)

x Power

~ Bandwidth
- Power and bandwidth affected by CNT conductivity

? Cost
- Cost changing rapidly



# Weight Savings Example

4km of CNT
Tape and Yarn

HALE UAV~ 385 kilograms of cable on board

- All CNT Cables Saves ~ 181 kg
- CNT Shield Alone Saves ~ 136 kg

Large Tactical Fighter ≈ 24 km cable on board

- All CNT Cables Saves ~ 896 kg
- CNT Shield Alone Saves ~ 535 kg

# CNT Characterization

Table 1. Material Types and Applications

# CNT Materials Characterized and Application

| Format(s) | Manufacturer | Materials | Application |
|---|---|---|---|
| Yarn | US Vendor A | CNT | Centre Conductor |
| Fibre | EU Vendor B | CNT | |
| Fibre | EU Vendor C | CNT | |
| | | | |
| Tape | US Vendor A | CNT | Shielding |
| Fibre | US Vendor D | CNT/Glass Fibre<br>CNT/Carbon Fibre | |
| Sheet | US Vendor D | CNT Composite | |
| Sheet | US Vendor E | CNT | |
| Tape | US Vendor F | CNT | |
| Powder | US Vendor G | CNT | |

Additional suppliers are also being evaluated.

Table 2. Material Characterization Testing

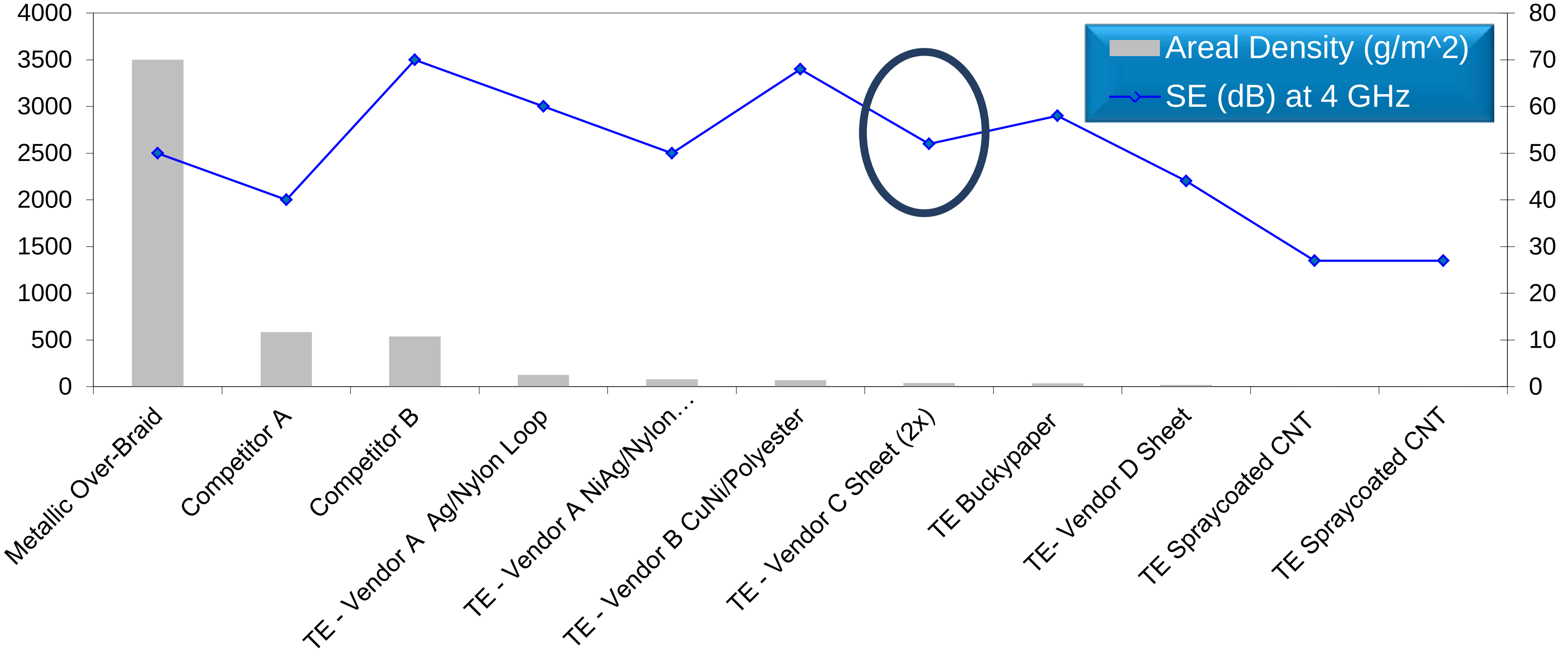
# Materials Characterization Testing

| Test | Format | Metric of Interest |
|---|---|---|
| Raman Spectroscopy | Yarn, Fibre | Carbon Nanotube Structure |
| Thermogravimetric Analysis | Yarn, Fibre | Composition |
| Scanning Electron Microscopy | All Formats | Morphology |
| Electron Dispersive Spectroscopy | All Formats | Composition |
| Tensile Strength | Yarn, Fibre | Mechanical Properties |
| Tear Strength | Tape, Sheet | Manufacturability |
| Conductivity | Yarn, Fibre | Electrical - DC |
| Impedance | Yarn, Fibre | Electrical - AC |
| Shielding Effectiveness | Sheet | Electromagnetic Interference Shielding |

# Shielding Effectiveness at 4 GHz (1 of 2)

Test Method: ASTM D4935, 1 – 8 GHz

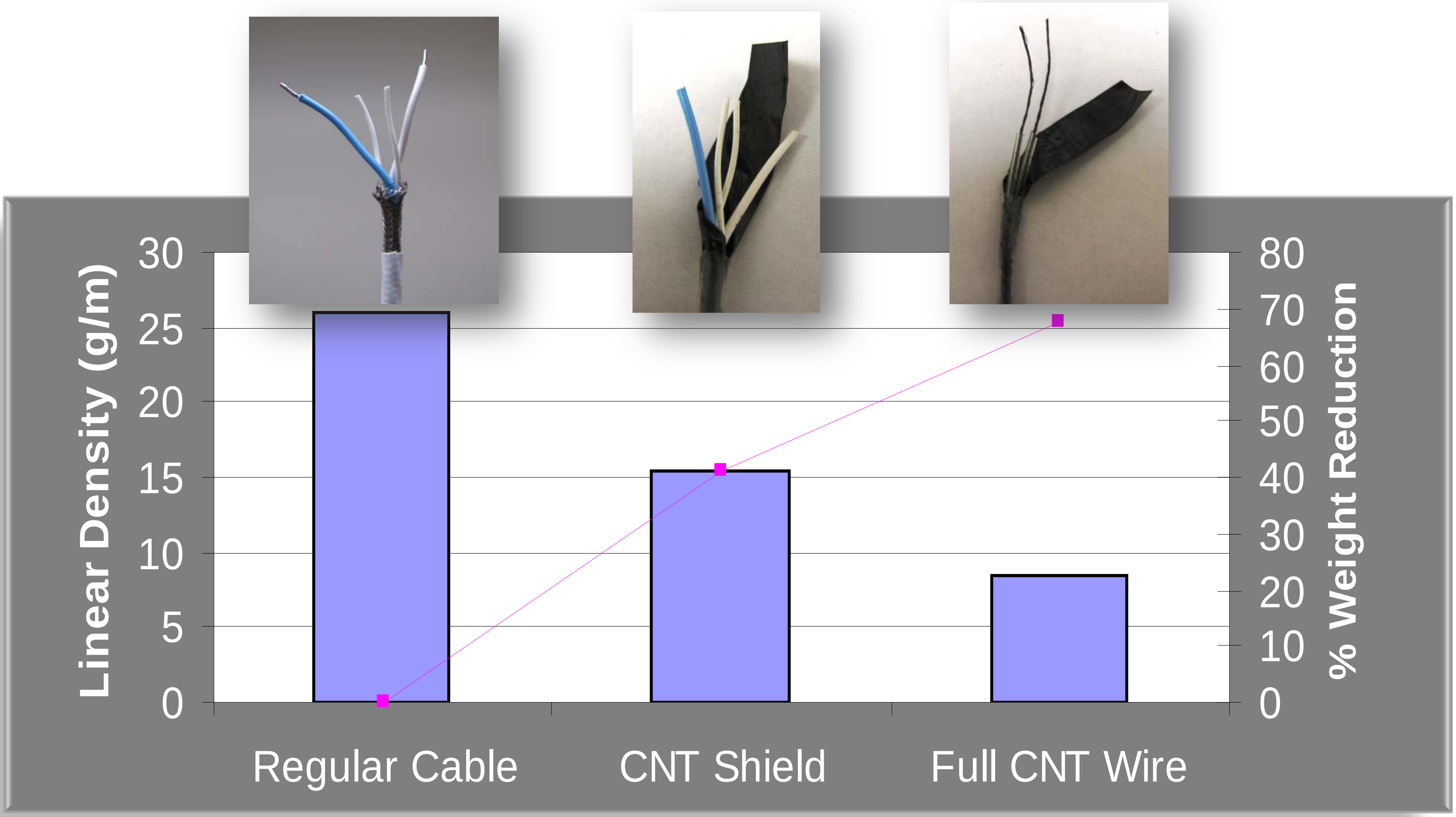
- Areal density (left Y axis)
- Shielding Effectiveness (right Y axis)




**Summary: Very good SE at 1-8GHz using CNTs**

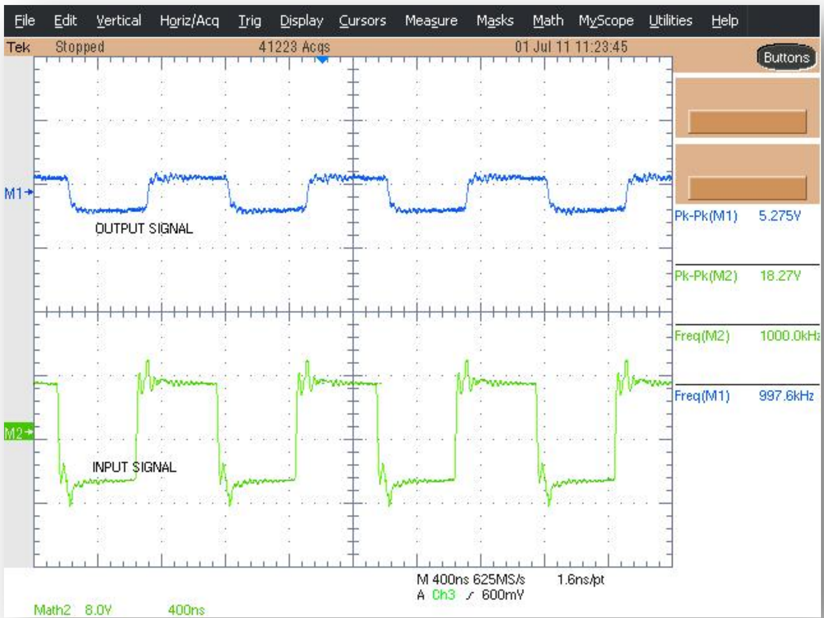
# Prototype Construction:  Twisted Pair (1 of 2)

Weight Savings Case Study:  69% Using All CNT construction



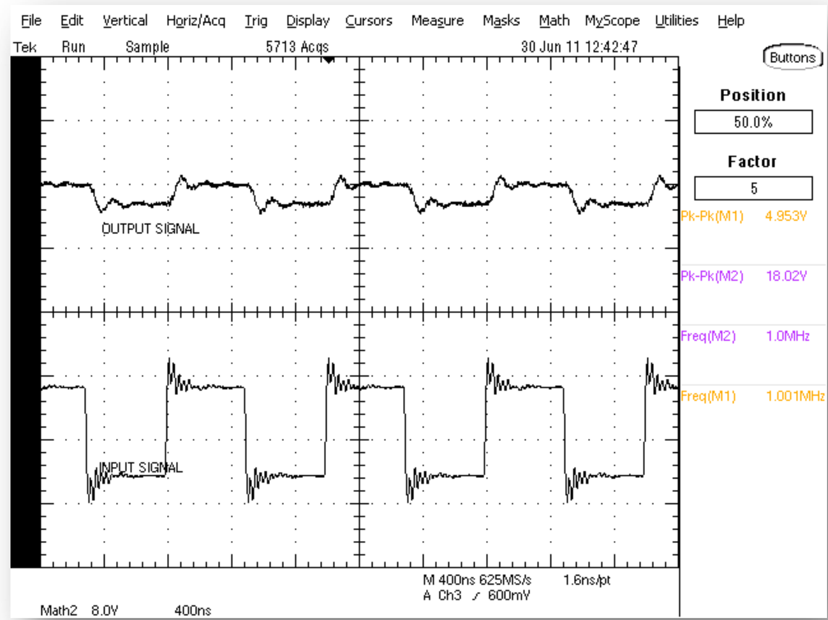
# Prototype Construction:  Twisted Pair (2 of 2)

## Word Test




Copper Databus Cable

12.995 Voltage Drop




CNT Databus Cable

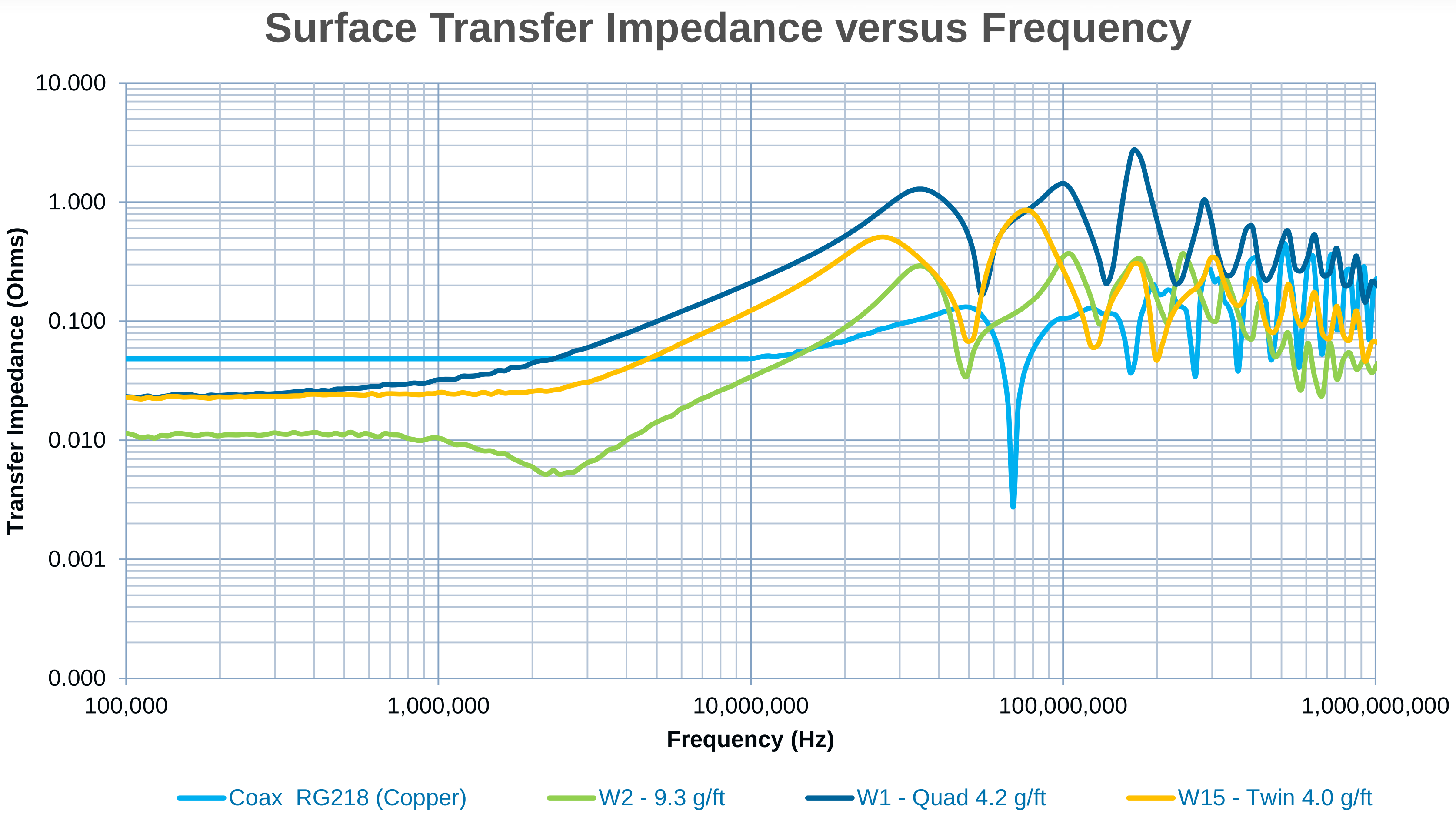
13.067 Voltage Drop

**Summary:  Performance comparable to standard cable using CNTs**

# Prototype Construction:  IEEE 1394 and RG-218

- CNT/Fiber Hybrid Material
- Braided Shield on IEEE 1394 core (FireWire)
- Good SE performance
- Prototypes have been flight-tested

# Cable Shielding –Flight Cables Constructed from CNT/Fiber




**Acceptable Performance at 10% or More Weight Savings**

TE connectivity

# CNT Prototype Line

# Prototype Development Line

Braider in Controlled Environment

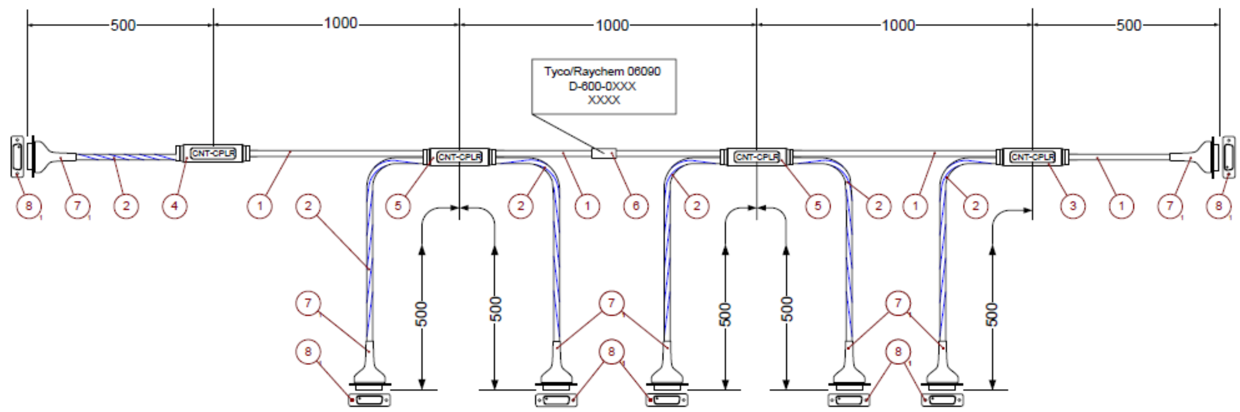
Twin-Screw Extruder

HEPA Filtration

3rd party air sampling indicates no airborne CNT release

# MIL STD 1553 Prototype

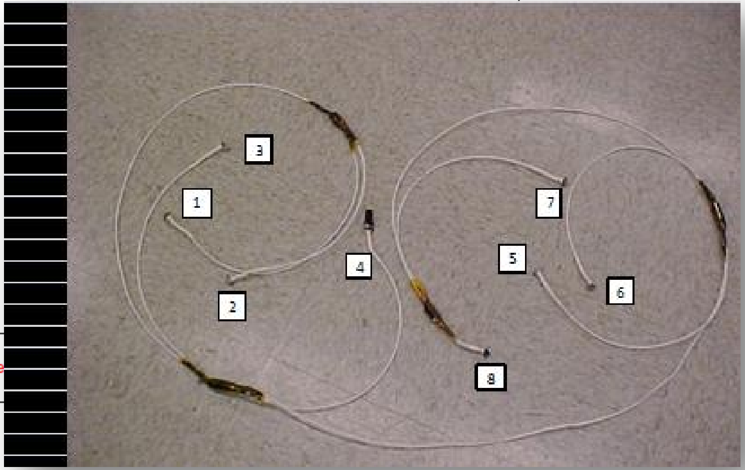
| | | | | |
|---|---|---|---|---|
| TE connectivity | Raychem Databus | CAGE CODE: 06090 | Title DATABUS CNT CABLE ASSEMBLY | Part Number D-600-0XXX |




**NOTES**

1. CONNECTOR MARKERS WHEN USED, ARE TO BE WITHIN 75mm OF THE CONNECTOR.
2. COUPLERS ARE TO MARKED AS SHOWN ON DRAWING.
3. HARNESS IDENTIFICATION MARKER IS TO BE POSITIONED CENTRALLY ON BUS LEG.
4. A TE SERIAL NUMBER IS TO BE ENTERED WHERE INDICATED XXXX, IN NUMERICAL SEQUENCE ON THE IDENTIFICATION MARKER.
5. ALL TMS IS TO BE MARKED ON BOTH SIDES.
6. THIS PRODUCT MEETS THE APPLICABLE REQUIREMENTS OF TE SPECIFICATIONS.
7. ALL DIMENSIONS ARE IN MILLEMETERS AND TOLERANCES ARE +/- 10.0 MM UNLESS OTHERWISE SPECIFIED.

| | | | | | | |
|---|---|---|---|---|---|---|
| Drawn By | GMR | G.Rositano | Product Manager | - | R.Watt | Project Databus Carbon Nano Tube |
| Technical Aprroval | - | E.Chen | Checked By: | GMR | G.Rositano | |



# Prototype Assembly Weight Breakdown

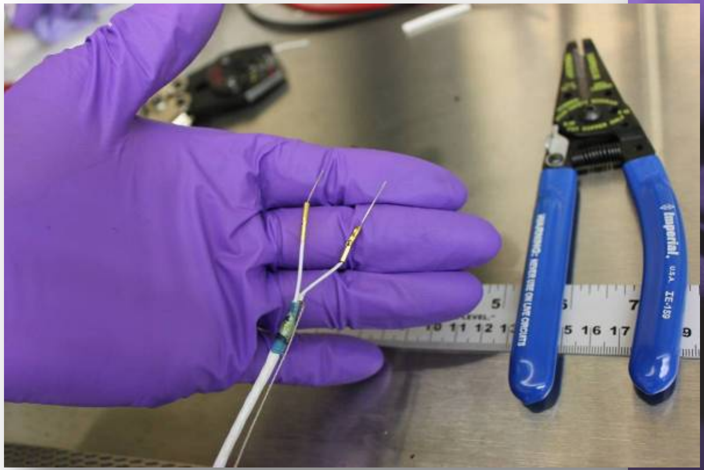
| | | | | | |
|---|---|---|---|---|---|
| NA | CNT Twisted pair with CNT Shield | 6.75 | meter | 6.68 | 45.09 |
| D-600-DBS-0047 | 1 Stub Coupler | 1.285 | part | 2 | 2.57 |
| NA | 1 Stub Coupler Enclosure | 1.365 | part | 2 | 2.73 |
| D-600-DBS-0049 | 2 Stub Coupler | 1.996 | part | 2 | 3.992 |
| NA | 2 Stub Coupler Enclosure | 2.028 | part | 2 | 4.056 |
| NA | Terminator Resistor 77 Ohm w enclosure | 3.356 | part | 2 | 6.712 |
| 1532209-1 | Micro-D Nickel Plated Plug | 1.64325 | part | 8 | 13.146 |
| 1532187-1 | Micro-D Nickel Plated recepticle | 1.682875 | part | 0 | 0 |
| D-094-05-10-03-01 | Gold Plated Crimps | 0.192 | part | 42 | 8.064 |
| D-436-36 | Miniseal (red 22-26AWG) | 0.1945 | part | 42 | 8.169 |
| S0175-3-01 | Shield Terminator | 0.4278 | part | 20 | 8.556 |
| RNF-100-1/4-9 | 1/4" white heat shrink tubing | 9.517 | meter | 3 | 28.551 |
| RNF-100-3/8-9 | 3/8" white heat shrink tubing | 12.579 | meter | 1 | 12.579 |
| NA | Coupler CNT shield + kapton tape | 1 | part | 4 | 4 |
| | | | | **Total** | 148.22 |

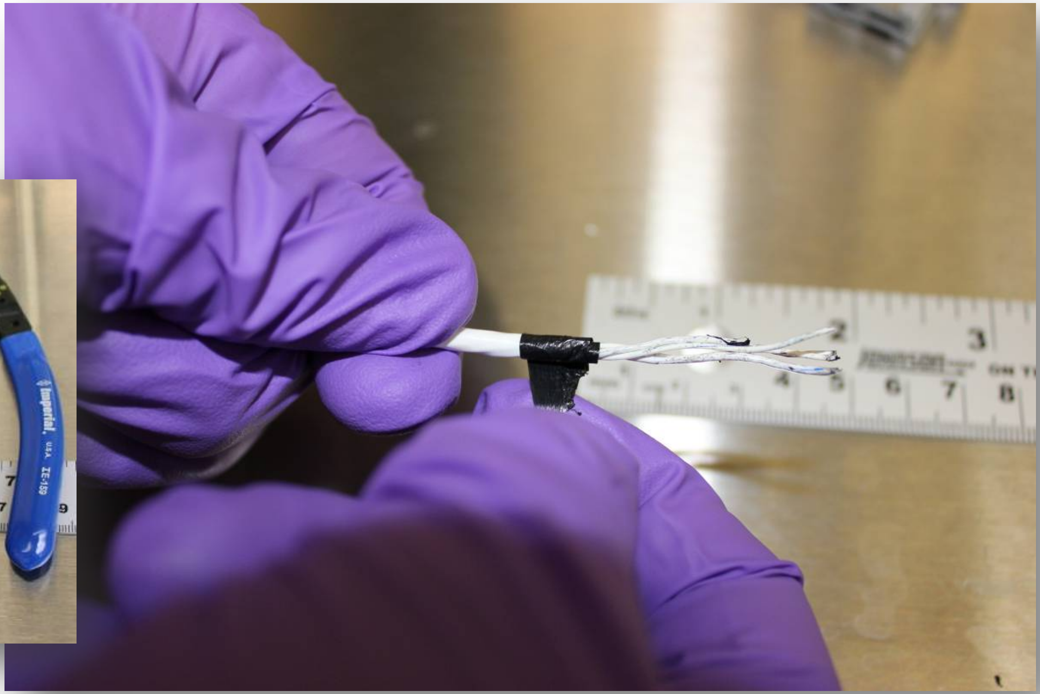
6.75 m CNT Twisted Pair with
Stubs, Micro-D, and Terminators = 148g
*Copper 1553B cable without terminations/coupler = 150g*

# CNT Termination

# All CNT MIL STD 1553 Cable Construction

- CNT yarn with ETFE extrusion
- CNT tape shielding
- Standard couplers

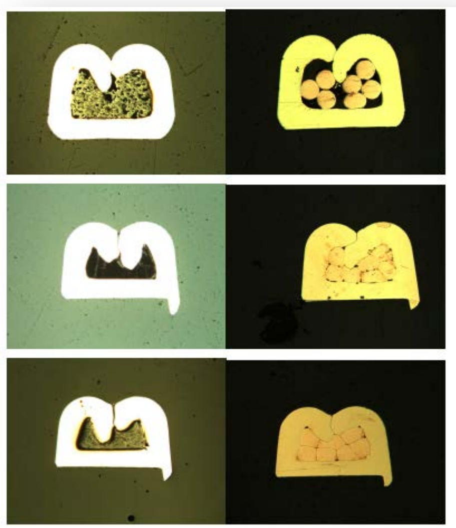




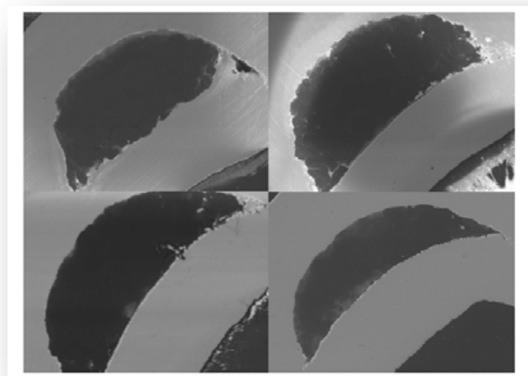
# CNT Termination (1 of 2)

## Standard Terminations Sufficient

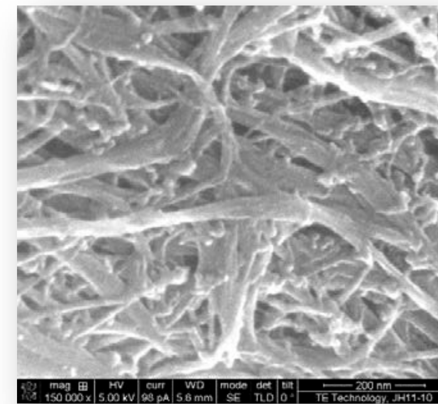
- No contact resistance issues due to inherent CNT resistance
- Mechanical crimp sufficient
- Soldering requires modification of CNT material

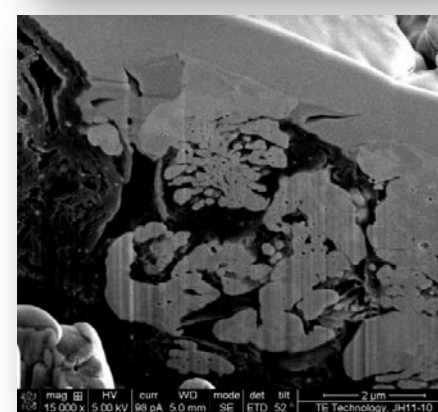


CNT and Cu
F Crimp Cross Section



CNT O Crimp
Successive Cross
Sections





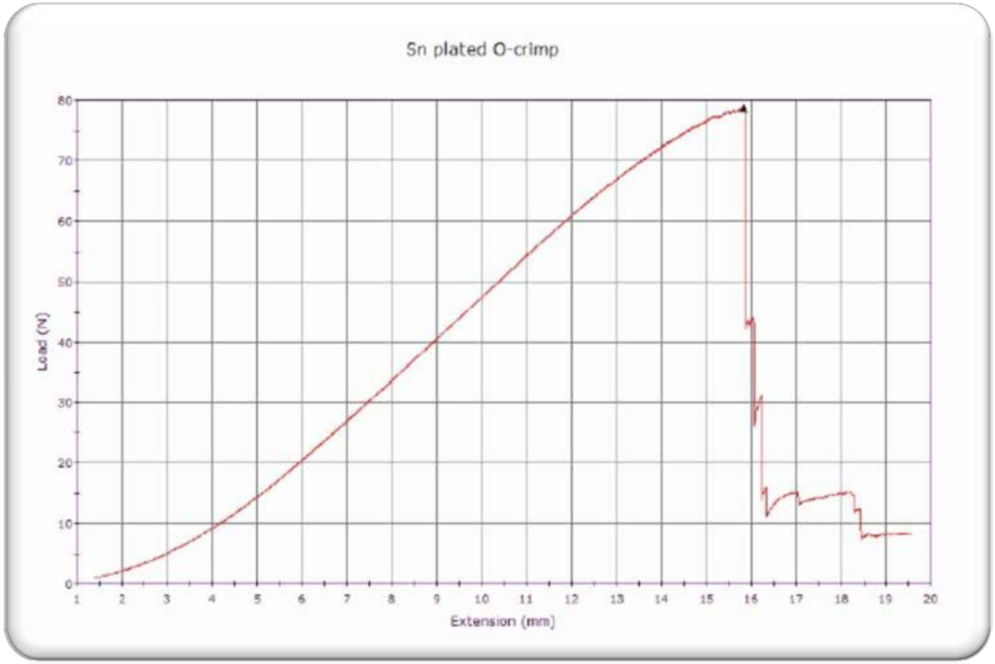
Plated CNT Yarn

# CNT Termination (2 of 2)

## Crimp Tensile Test Results

- CNT yarn fails before pull out
- Values consistent with CNT yarn tensile strength

Tensile Test Set-Up




Sn Plated O Crimp (24 AWG Yarn)
Average Load to Failure = 78.7N +/- 0.6N

# Preliminary Electrical Characterization

# Rise Time Optimization Sample Descriptions (1 of 2)

- All cables approximately 24 AWG
- Customer also sought diameter reduction
- Shield variation
  - CNT (tape)
  - Hybrid CNT tape + Cu Serve shield
  - Copper Braided Shield
- Dielectric variation
  - ETFE
  - Foamed FEP

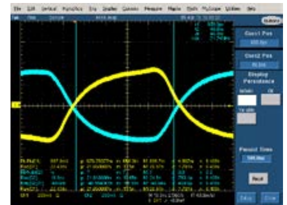
# Rise Test Results:

| Cable | Construction Weight (g/m) / (lb/kft) | Rise Time at 1MHz (ns/ft) |
|---|---|---|
| 1. **CNT** Conductor, ETFE Dielectric, CNT Tape Shield | 9.06 / 6.08 | 2.066 |
| 2. Cu Conductor, ETFE Dielectric, **CNT** Tape Shield | 18.51 / 12.43 | 0.449 |
| 5. Cu Conductor, foamed FEP Dielectric, Cu Braided Shield | 25.94 / 17.53 | .00027 |

# Pseudo Eye Patterns: Differential square wave input (5ns rise time) Cable output waveforms

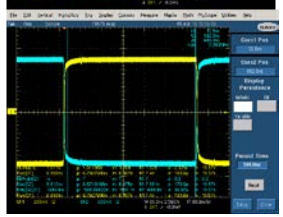
1MHz | 10MHz

1. CNT Conductor, CNT Tape Shield(5.11m)



2. Cu Conductor, CNT Shield (1.84m)

3.Cu Conductor, Cu Braid Shield(5.11m)

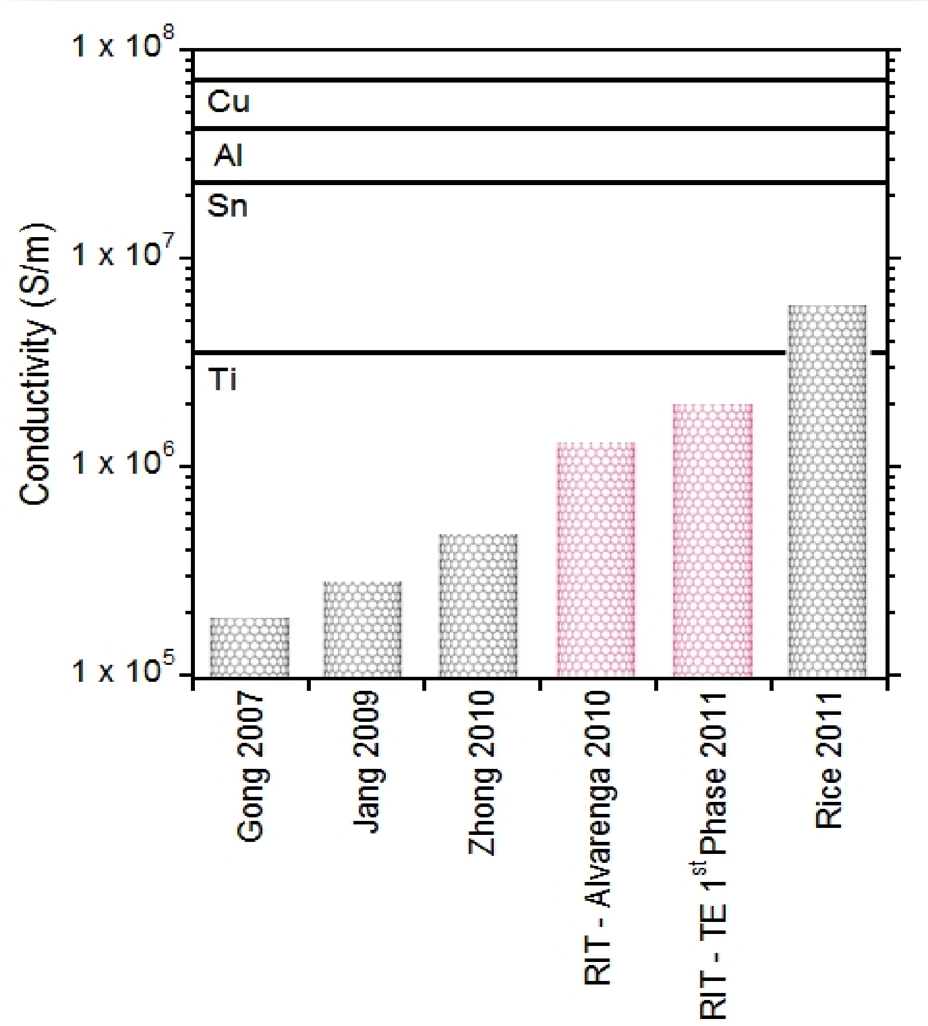


All CNT construction versus all Cu provides a **64%** weight reduction with acceptable signal loss for low-bandwidth applications.

# Conductivity Comments

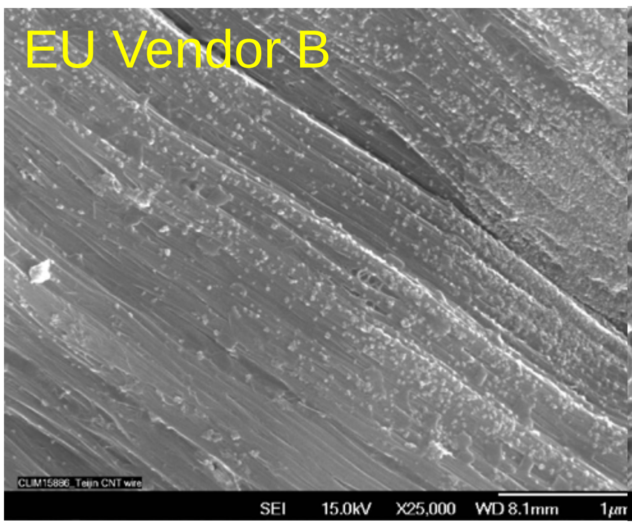
# Conductivity Improvements

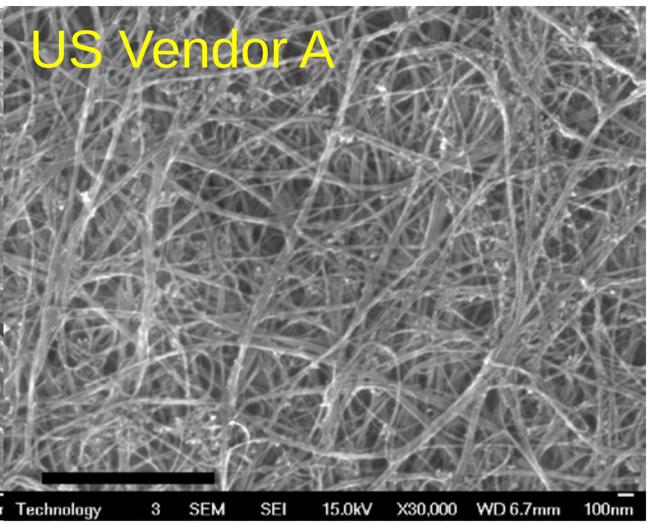
TE has sponsored research into CNT conductivity improvement.



# Conductivity: Networks versus Individual Tubes

- Traditional CNT conductivity models are based on few CNT systems
  - Ballistic conduction
  - Quantum tunneling
- Macroscopic format are billion/trillion CNT networks
  - Tunneling at junctions vs contact resistance at junctions
  - Network morphology plays a role



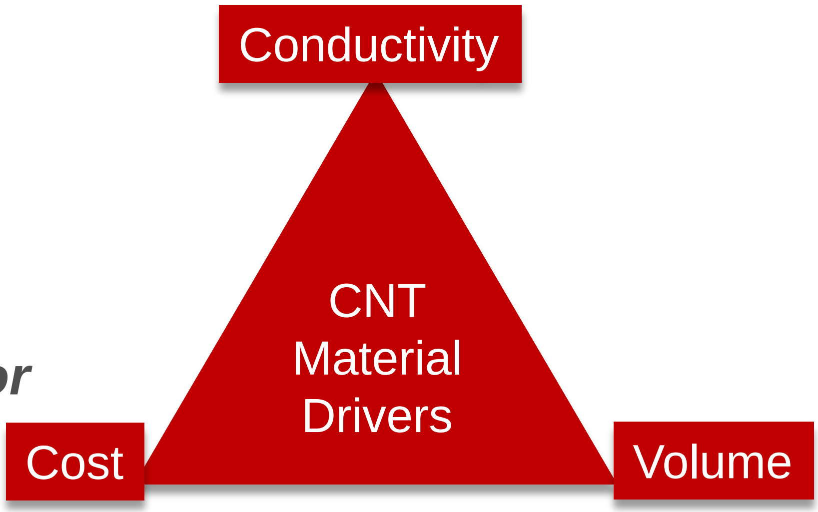




Network morphology can influence CNT conductivity by three orders of magnitude.

# Summary

# Summary

- CNT materials promising for SWaP
  - Shielding (all cable types)
  - Data Communication
- Current CNT macroscopic materials not sufficiently conductive as ***centre conductor*** for all cable applications
  - Co-axial Cables
  - Power Cables
- Standard Terminations are Acceptable
- Prototype Line on Existing W&C Equipment




The type of CNT material used for a given application is a balance of required **conductivity**, **cost**, and **availability**.


ESA-ESTEC Passive Component Days 2013
THANK YOU
Questions?