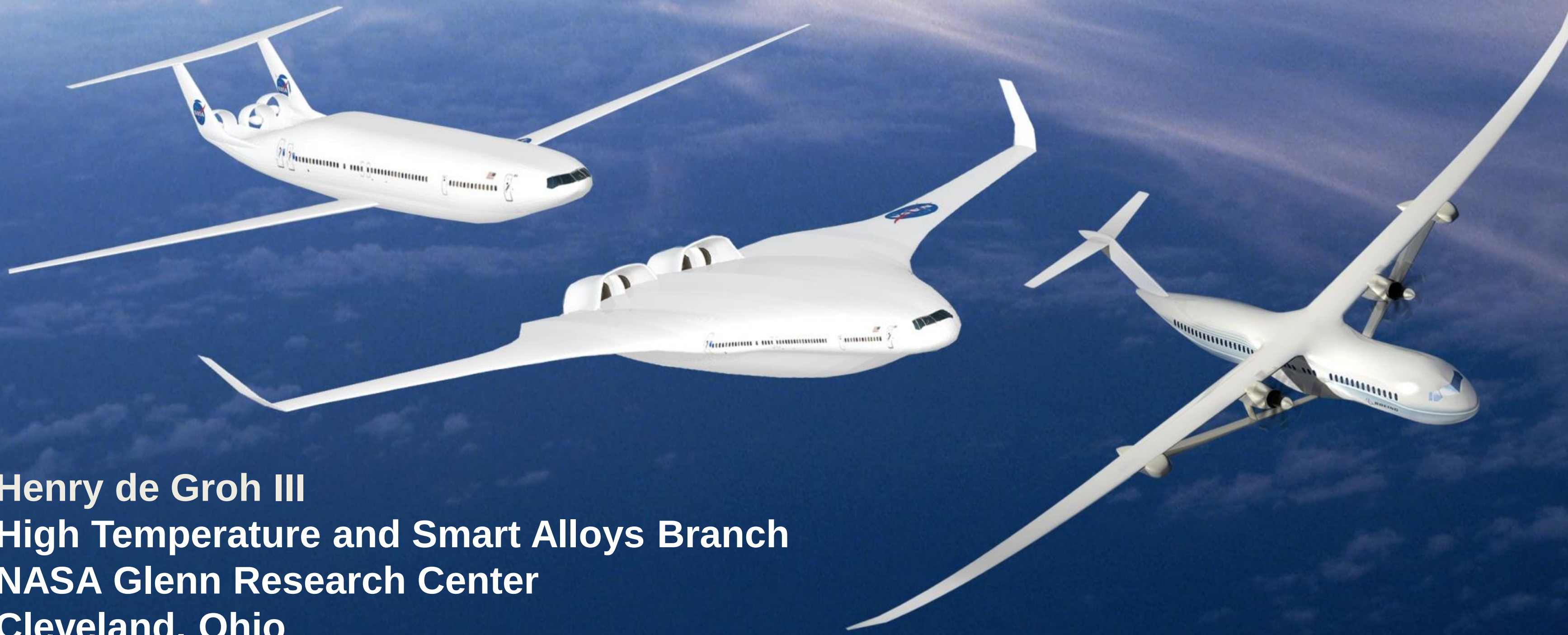
Carbon Nanotube Composite Ampacity and Metallic CNT Buckypaper Conductivity

MRS Fall Meeting
Symposium NM$_3$- Nanotubes and Related Nanostructures



Henry de Groh III
High Temperature and Smart Alloys Branch
NASA Glenn Research Center
Cleveland, Ohio

Dec. 1, 2016

Background and Motivation

Compared to baseline aircraft 7% to 12% fuel reduction depending on mission; aft motor resulting in boundary layer ingestion.

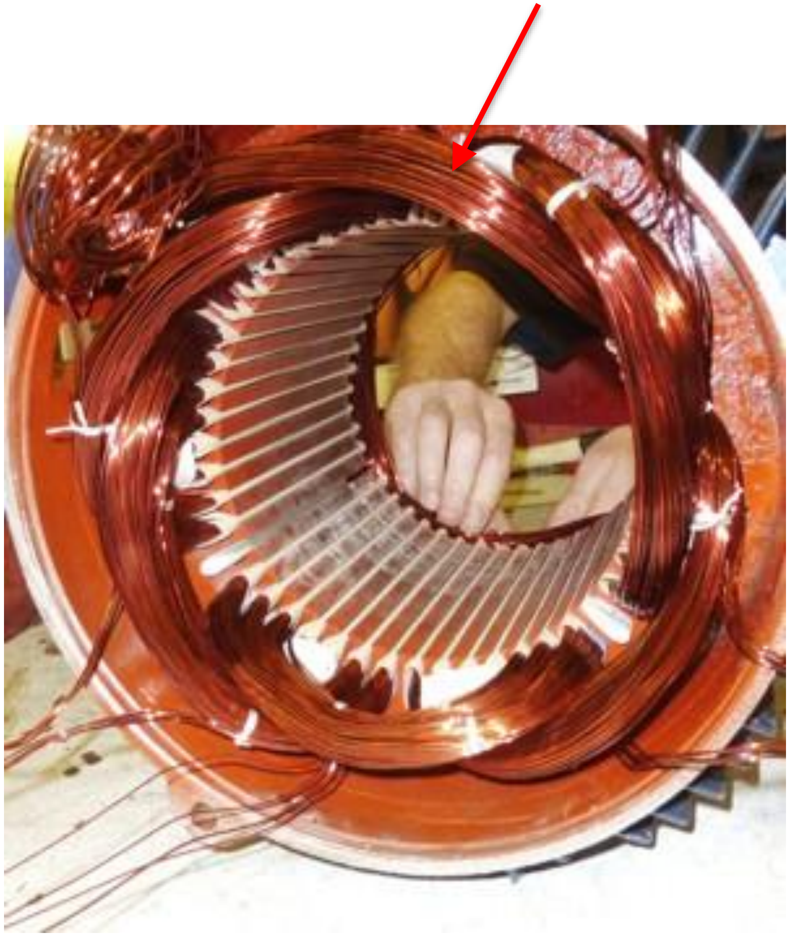
Electric Motor	8 hp/lb	96%	3500 hp	437 lbs
Inverter	10 hp/lb	98%	3500 hp	350 lbs
Generator 2	8 hp/lb	96%	2@1937 hp	484 lbs
Cable 2 x 93' @ 750 V / 1926 amps	3.85 kg/m	99.6%	1.44 MW	482 lbs
Circuit Protection	0.5 * Cable Wt			240 lbs
Thermal Management System (ROM)	0.68 kW(th)/kg	279 kw(th)		906 lbs
Total Electrical + TMS				2921 lbs

Passengers: 154
Range: 3500 nm
Cruise Speed: Mach 0.7

Welstead et al., Presented at AIAA Sci Tech Jan. 2016

Background and Motivation

Improvements in Magnet Wire.



Program Goals

- Increase Motor Wire Conductivity
  - Lower i^2R losses;
  - Lower cooling requirements;
  - Higher power-to-weight ratio.
- Lower Wire Density

Experimental Procedures and Goals

- Ampacity (current/unit area, A/cm^2);
  - To test claims of high current carrying capacity of CNT-Cu composite wire.
- Raman Spectroscopy of CNT sources;
  - To develop metallic and semiconductor CNT characterization methods.
- Buckypaper Resistivity;
  - To test the dependence of resistivity on CNT characteristics: metallic vs. semiconductor.

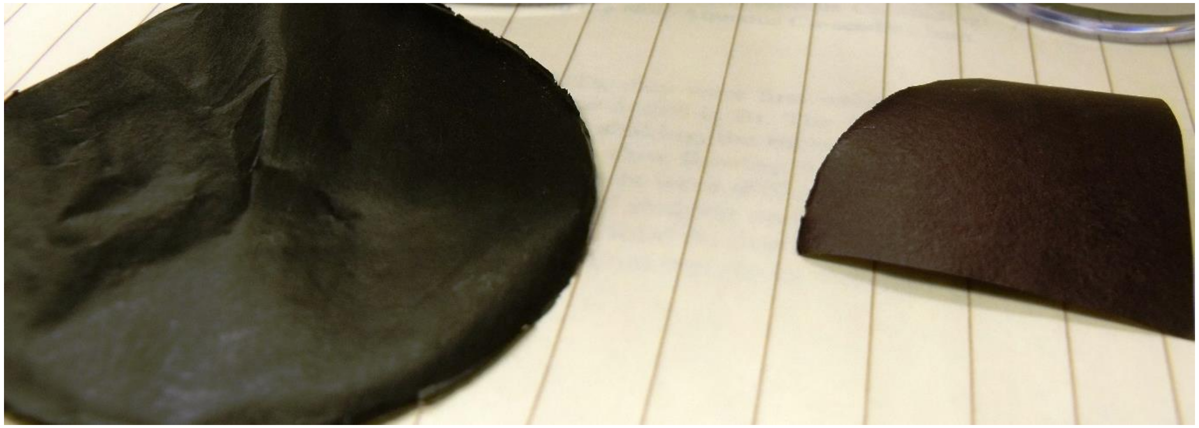
Experimental Procedures- Ampacity

- Ampacity = max Amp/cm^2
  - 20 AWG pure Cu magnet wire;
  - 20 AWG Cu-5vol%CNT composite wire from NanoRidge Materials Incorporated;
  - 28 AWG MWCNT yarn from Nanocomp Technologies.

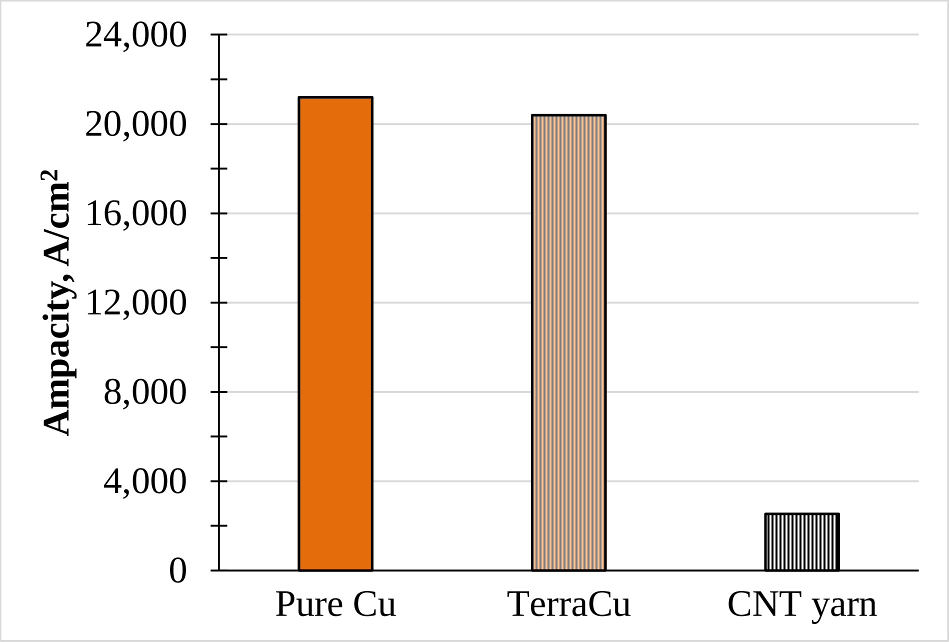
Experimental Procedures- Raman Spectroscopy

- Samples
  - <u>MWNT</u>- Multi-wall CNT Buckypaper m-CNT:s-CNT ratio debatable.
  - <u>FWNT</u>- few-walled CNT, by Southwest NanoTechnologies,reported to be metallic.
  - <u>Mixed SWNT</u>- Super PureTubes 66% s-SWNT:33% m-SWNT.
  - <u>Sorted SWNT</u>- IsoNanotubes-M (95%) claimed to be 95% m-SWNT.

- Raman Spectroscopy conditions
  - wavelength λ = 633 nm, 3500 cm^{-1} upper cutoff, laser powers 2 to7 mW.
  - Top, bottom, different areas.
  - Examined G-band, D-band, G'-band, RBM.



Results- Ampacity

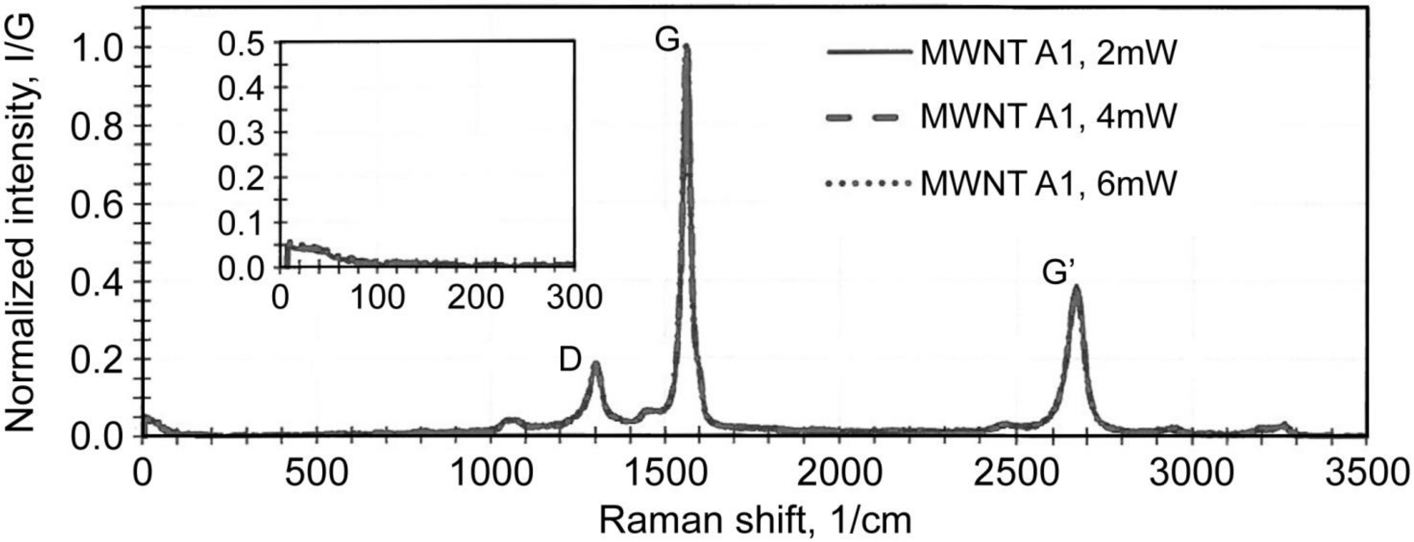


Low longitudinal cooling is required to yield realistic results.

Average of 2 or 3 Ampacity measurements of Pure Cu, Cu-CNT composite TerraCopper, and a CNT yarn.

Results- Raman Spectroscopy

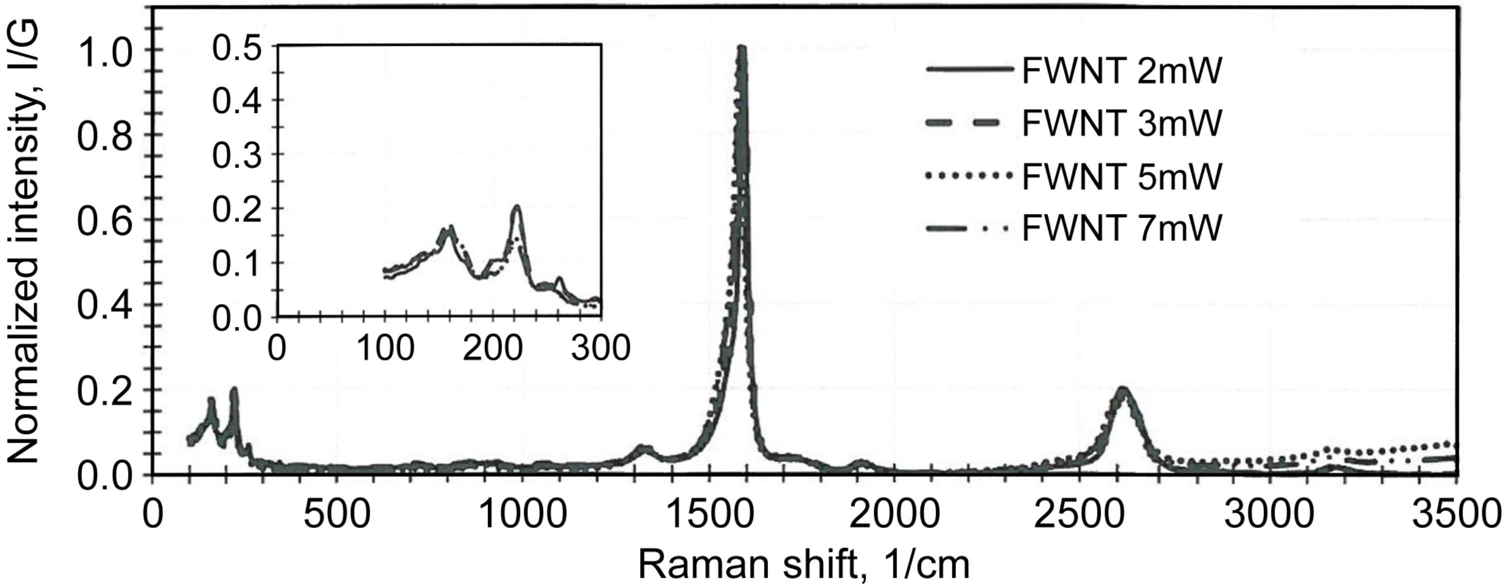
MWNT Buckypaper: Lorentzian G-band peak, no RBM, low D-band and G’-band intensities.



Results- Raman Spectroscopy

FWNT Powder:

- Lorentzian G-band peak;
- RBM: Strong 221 ((13,1) or (11,4)) and 158 cm^{-1} peaks; Weak peaks near 198 ((14,2) or (12,5)) and 172 cm^{-1} (18,0). [1,2,3]
- Low D-band and G'-band intensities.

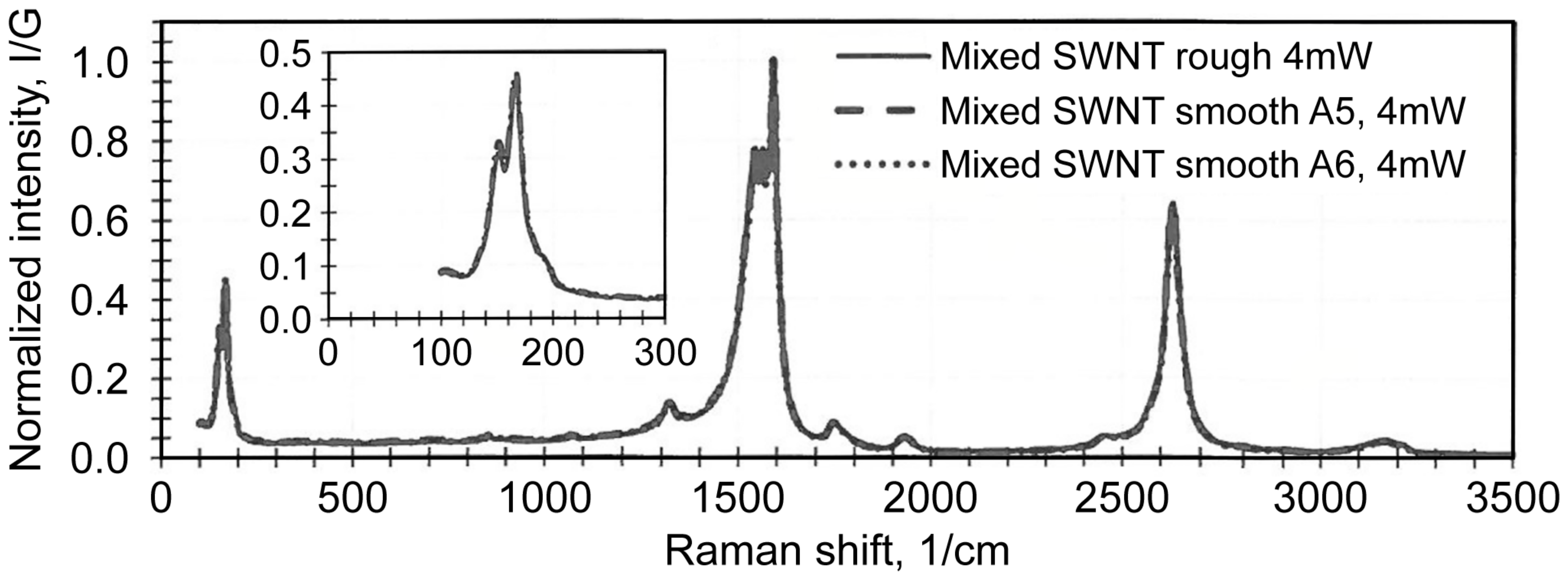


[1]Baik et al. J. Phys. Chem. B. Vol. 108, No. 40, 2004. [2]Hennrich et al. J. Phys. Chem. B, Vol. 109, 2005. [3]Maultzsch et al. Phys. Rev. B, Vol. 72, 205438, 2005.

Results- Raman Spectroscopy

Mixed SWNT:

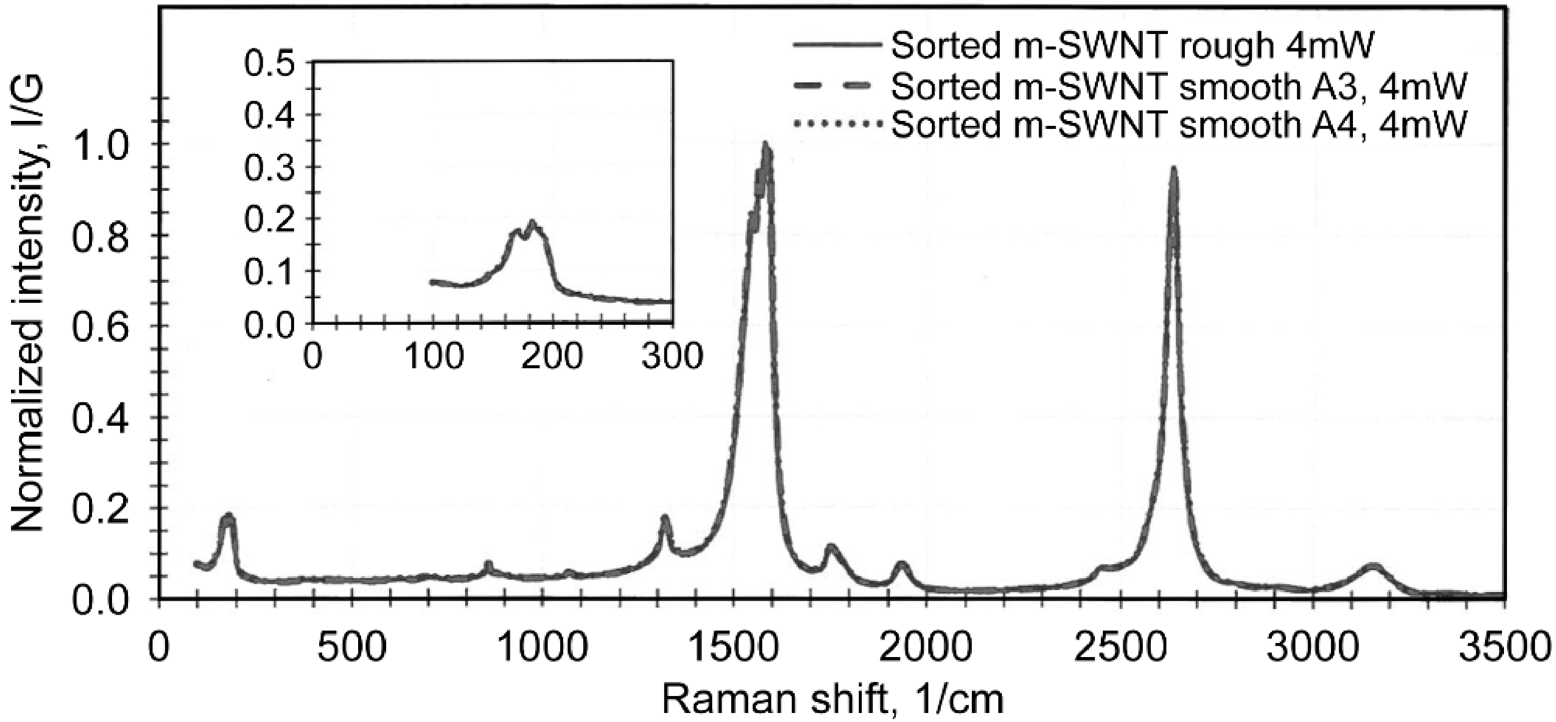
- Breit-Wigner-Fano (BWF) G-band line shape;
- RBM: 192 (11,7) or (12,6), 167 and 152 cm^{-1};
- Low D-band and moderate G'-band intensity.



Results- Raman Spectroscopy

Sorted SWNT:

- Breit-Wigner-Fano (BWF) G-band line shape;
- RBM: 181 (15,3), 196 (13,4), 200 (14,2) cm^{-1};
- Low D-band and high G'-band intensity.



Results- Raman Spectroscopy

Table I.—Average Raman Shift peak ratios; the average % standard deviation for all measurements was 2.8%.

Sample, # of samples in average	**G/D**	**G/G'**
MWNT, 3	5.44	2.62
FWNT, 5	16.0	5.32
Mixed SWNT, 3	7.20	1.60
Sorted m-SWNT, 11	6.06	1.00

Results – Buckypaper Resistivity

Mixed SWNT – $\rho_{mixed} = 0.00296$ Ohm-cm

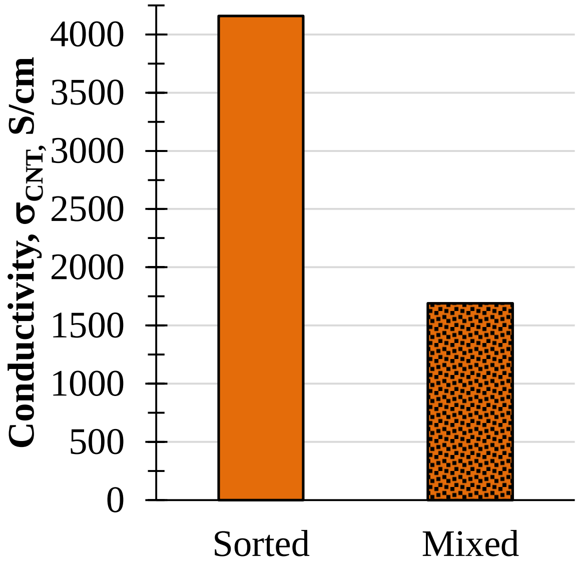
Sorted SWNT – $\rho_{sorted} = 0.0019$ Ohm-cm

10 to100 times lower resistivity than others found in the literature; due to the cleanliness of the CNT which enables good, low resistance contacts among CNT.

$$\text{Conductivity} = \sigma_B = 1/\rho_B = \sigma_{CNT}(\varphi_{CNT}) + \sigma_{void}(\varphi_{void})$$

where σ_{void} is void conductivity which is set to zero, and φ is volume fraction.

σ_{CNT} includes interfacial resistances and is not the intrinsic conductivity of the CNT.



Conclusions

- Improvement of ampacity was not achieved by adding 5vol% CNT to Cu;
- Raman spectroscopy and G/G' provide indications of metallic CNT;
- A measure of m-CNT:s-CNT might be possible for a give batch subjected to sorting;
- Clean, unfunctionalized SWNT yielded unusually high Buckypaper conductivities. The conductivity of sorted SWNT BP 246% higher than unsorted, which implies conductivity improvements can be achieved through the use of sorted m-CNT.

Current & Future Work