# Materials selection for wire scanner wires

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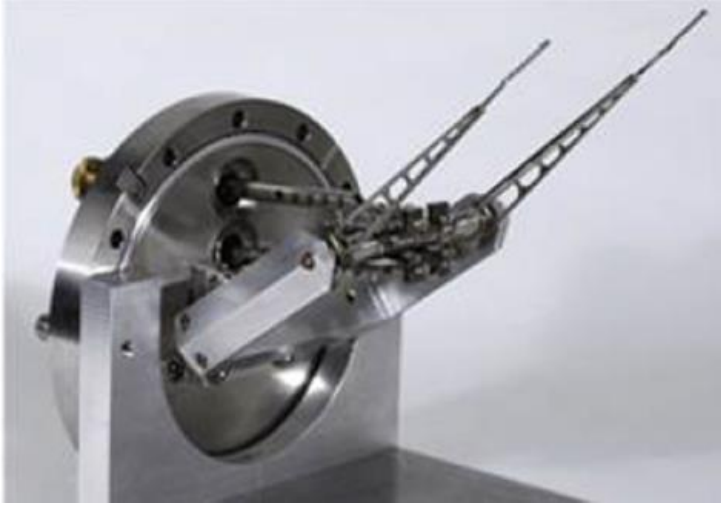
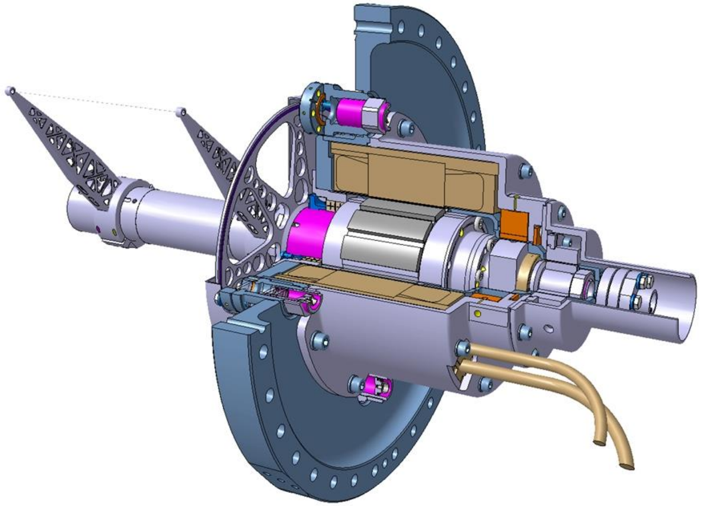
Part I: Material selection – "How do we know what is the right material for the wire?"
Part II: Investigating CNT wires – damage tolerance and reliability.

# Part I: Material selection

## Typical wire scanner designs





**Purpose**

To measure beam position and distribution

Calibration of other systems for beam positioning

**Operation**

Wire is held in tension on compliant fork arms.

Wire traverses the particle beam, producing a particle shower.

Downstream particle shower is detected.

Wire position is known from position encoders.

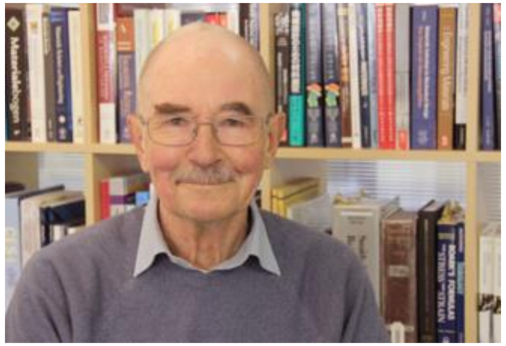
**Challenges**

Intense heating while under mechanical load

Increasing demands from LHC (energy, flux)

Resolution limits

# Ashby materials selection method

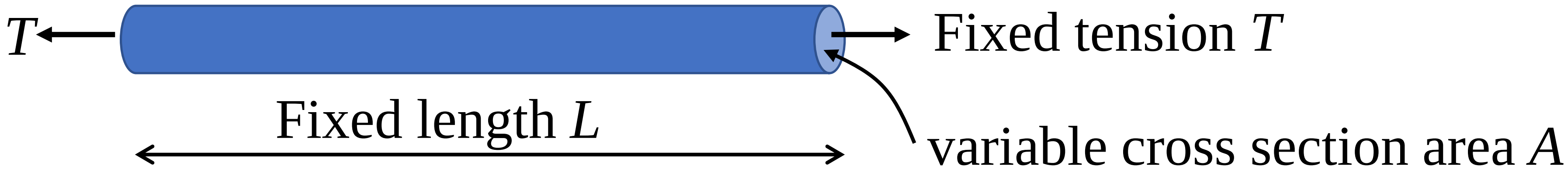


Mike Ashby

1. Identify key design *objective* and *constraints*
2. Model the physical system
3. Express the constrained objective in terms of material properties
4. Identify a *Material Index* –

   "the property or group of properties that maximises performance for a given design"

## Example – a light, strong tie rod




Relevant material properties:

Failure strength: $\sigma_f$

Density: $\rho$

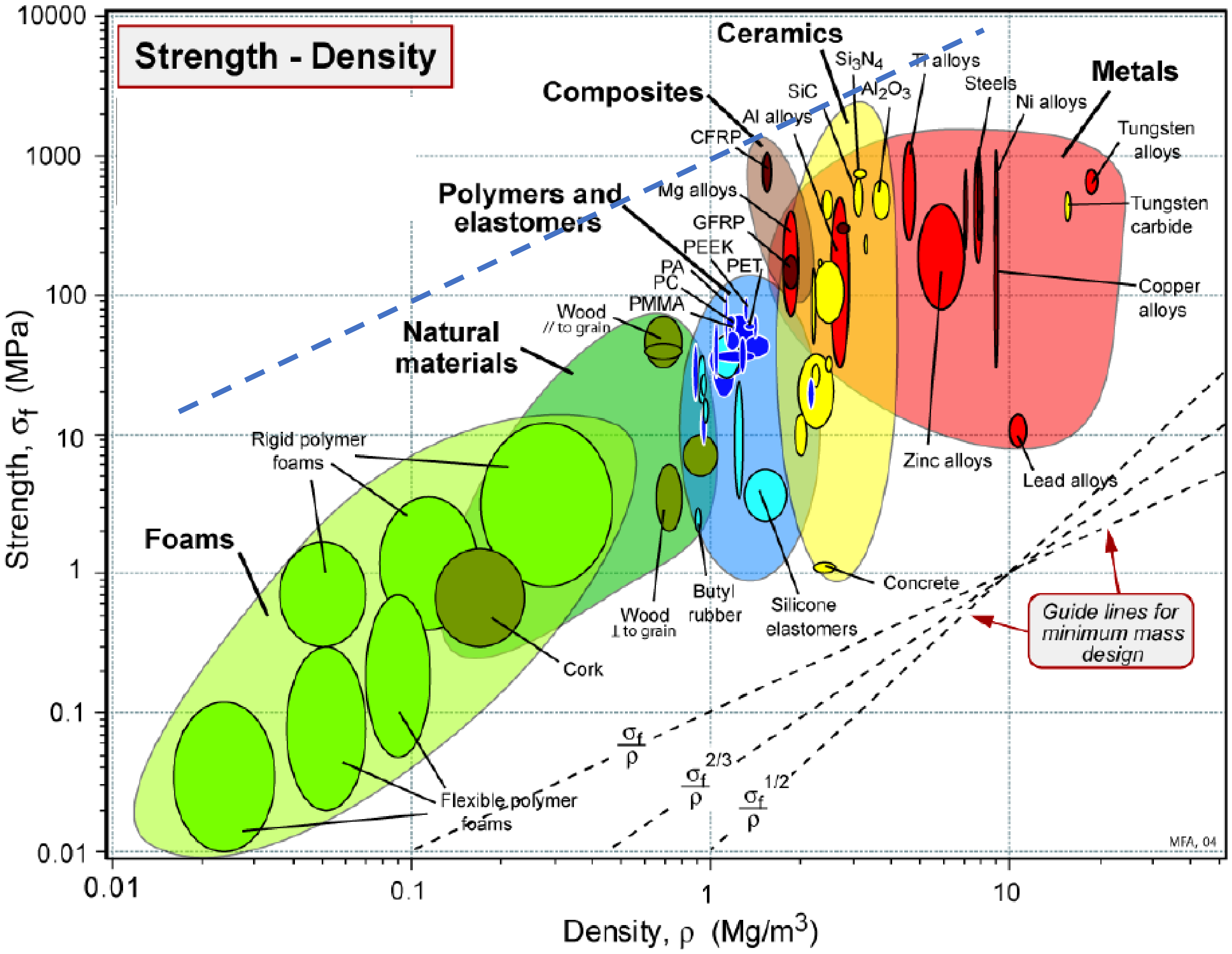
# Example – a light, strong tie rod

*Objective*,
minimize mass: $m = \rho L A$

*Constraint* on strength: $\frac{T}{A} \leq \sigma_f$

Eliminate *A*: $m \geq \left(\frac{\rho}{\sigma_f}\right)(LT)$

*Material Index:* $\frac{\sigma_f}{\rho}$




*Observation: The analysis is greatly simplified with approximations and assumptions, yet, it is successful in revealing the key requirements for optimal materials.*

# The wire scanner problem – choosing a wire material

*Objective*: Scan the greatest power hadron beam without "failure"

Beam power:

$$P_{\text{beam}} = \underbrace{\dot{n}}_{\text{particle flux}}\underbrace{E}_{\text{particle energy}}$$

*Constraints*:

(i) Peak temperature must not exceed a limit temperature for the material

$$T_{\text{p}} < T_{\text{max}}$$

(ii) Mechanical stress in the wire must not exceed failure stress

$$\sigma_{\text{p}} < \sigma_{\text{max}}$$

(iii) Deflection of the wire must not exceed a definite resolution limit

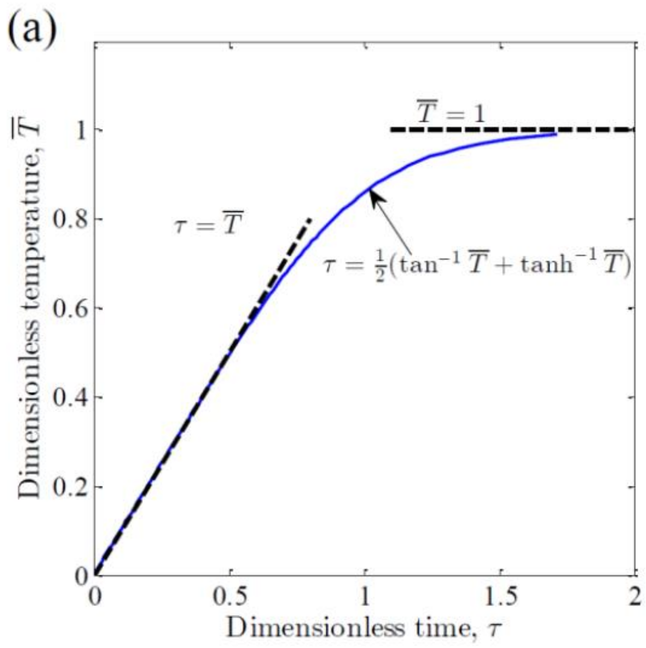
$$\delta_{\text{p}} < \delta_{\text{max}}$$

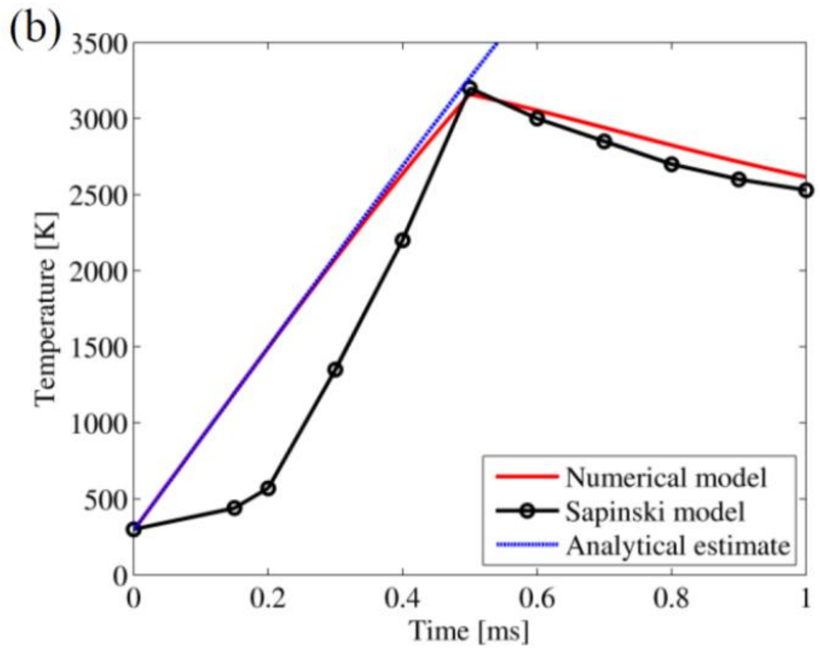
See: Bigland, H. et al. (2019) Advanced Engineering Materials 22 (3), 1900927

# The wire scanner problem – connecting the constraints

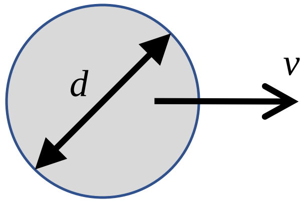
*Thermal constraint:* $T_{\mathrm{p}} < T_{\max}$

Thermal model: $$P = \rho V c_{\mathrm{p}}(T)\frac{\partial T}{\partial t} + A_{\mathrm{rad}}\varepsilon\sigma\left(T^4 - T_{\mathrm{amb}}^4\right) + P_{\mathrm{cond}} + P_{\mathrm{th}} + P_{\mathrm{cur}} + P_{\mathrm{sub}}$$




Peak temperature estimate: $$T_{\mathrm{p}} = \frac{4P}{\rho c_{\mathrm{p}} \pi d^2 v}$$




Wire cross-section

# The wire scanner problem – connecting the constraints

To relate the absorbed power $P$ to the beam power $P_{beam}$ we used restricted stopping power calculations in FLUKA* from which, approximately:

$$P = \frac{\dot{n}}{\pi D^2/4} \frac{\mathrm{d}E}{\mathrm{d}x} D \pi d^2/4 = \frac{P_{\mathrm{beam}}}{ED} \Omega \rho d^2$$

*Where*

$E$ is the particle energy

$D$ is the beam diameter, and

$\Omega$ is the restricted stopping power per unit density, or "mass stopping power".

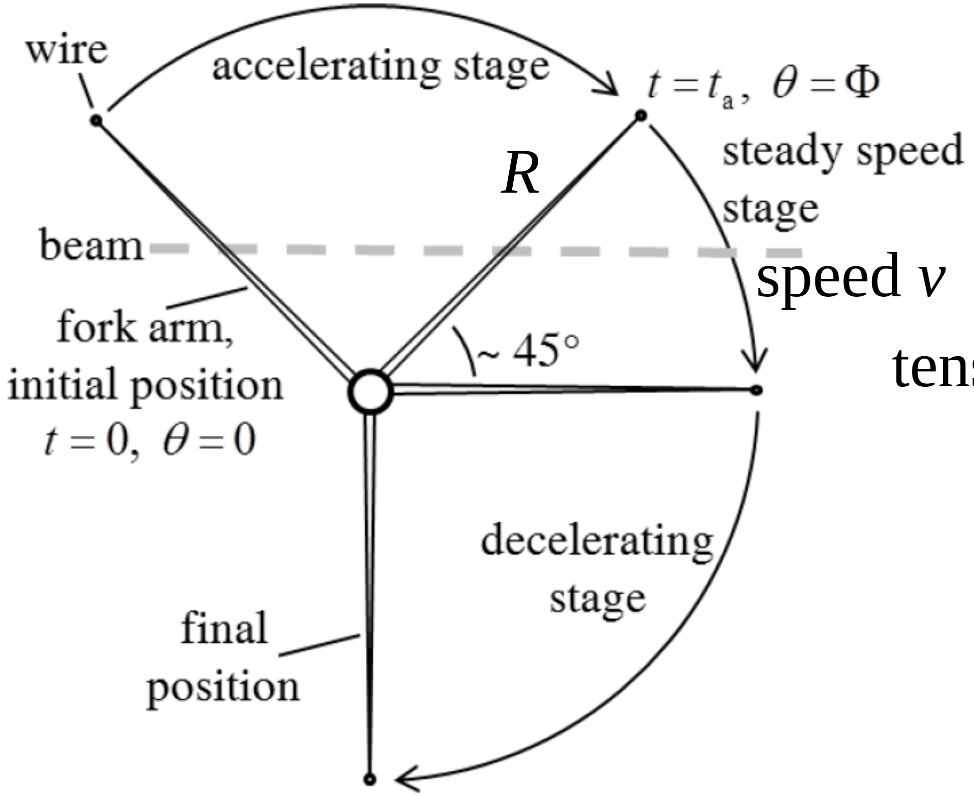
Consequently the peak temperature can be written as:

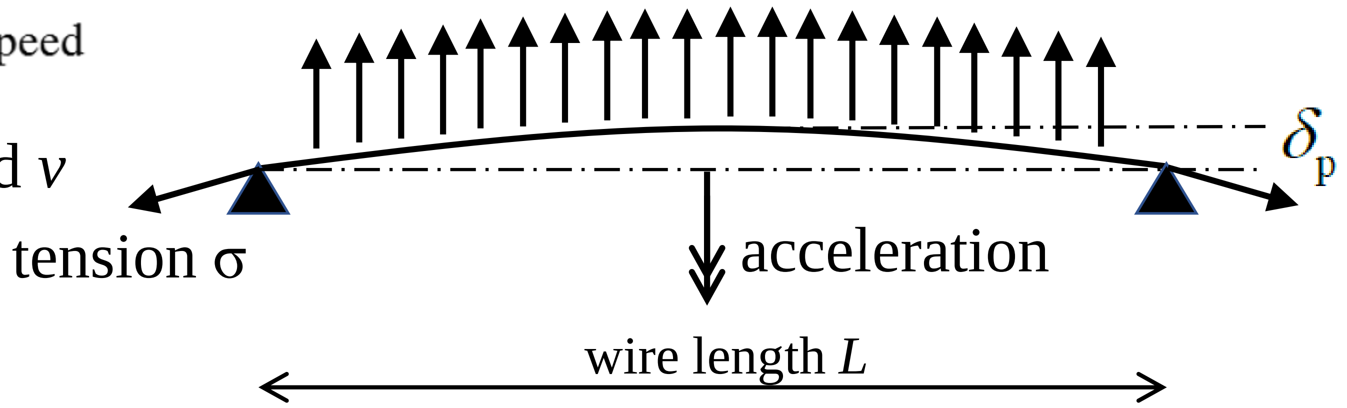
$$T_{\mathrm{p}} = \left(\frac{4 P_{\mathrm{beam}} \Omega}{\pi E D}\right)\left(\frac{1}{\nu c_{\mathrm{p}}}\right)$$

*Acknowledgement to Anton Lechner for conducting FLUKA calculations

# The wire scanner problem – connecting the constraints

*Mechanical constraints:* $\sigma_{\mathrm{p}} < \sigma_{\max}$ *and* $\delta_{\mathrm{p}} < \delta_{\max}$




For typical designs: $$\delta_{\mathrm{p}} = \frac{\rho v^2 L^2}{8R\sigma}$$

# The wire scanner problem – Material Index

Thermal constraint: $$T_{\mathrm{p}} = \left(\frac{4P_{\mathrm{beam}}\Omega}{\pi ED}\right)\left(\frac{1}{v\mathrm{c}_{\mathrm{p}}}\right) < T_{\max}$$

Mechanical constraint: $$\frac{\rho v^2 L^2}{8R\sigma_{\mathrm{f}}} = \delta_{\mathrm{p}} < \delta_{\max}$$

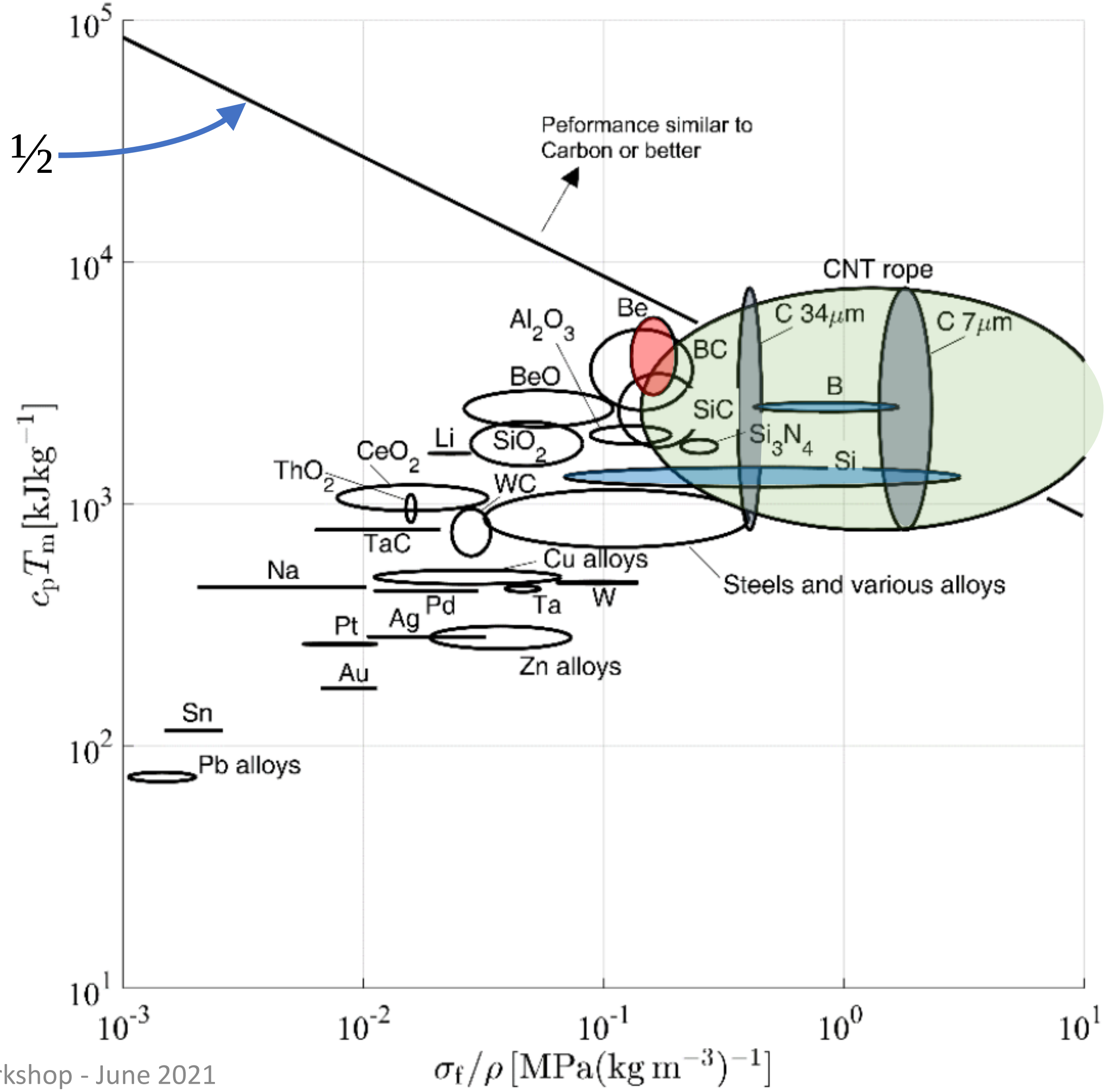
Treat scanning velocity *v* as a free variable:

$$P_{\mathrm{beam}} < \underbrace{\left(\frac{\pi ED}{\Omega\sqrt{2}}\right)}_{\text{Physical constants and LHC parameters}}\underbrace{\left(\frac{\sqrt{R\delta_{\max}}}{L}\right)}_{\text{Wire scanner design parameters}}\underbrace{\left(\mathrm{c}_{\mathrm{p}}T_{\max}\sqrt{\frac{\sigma_{\mathrm{f}}}{\rho}}\right)}_{\text{material merit index}}$$

# The wire scanner problem – Material Selection Chart

Observations:

slope = - ½




Analysis confirms Carbon as a high performance material

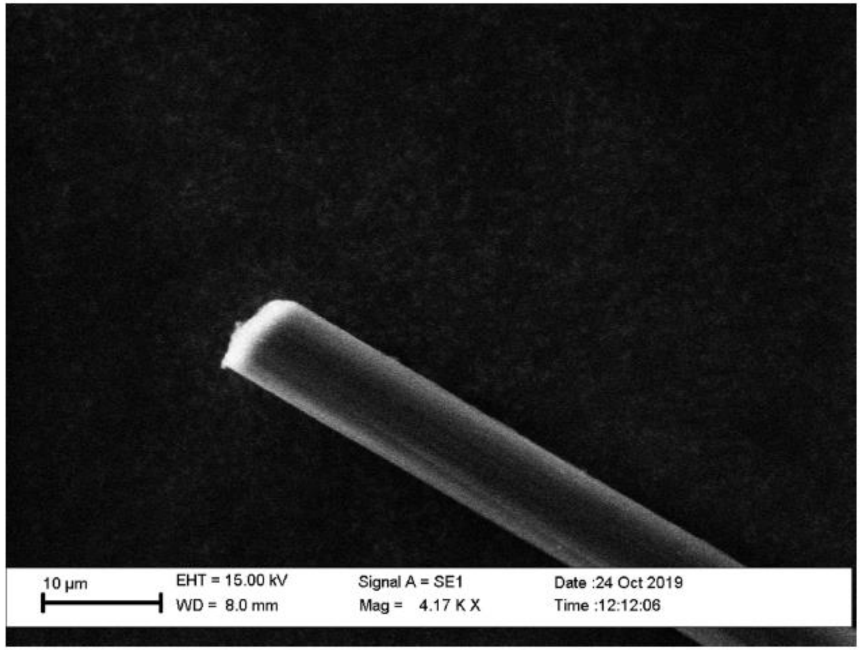
Other options such as Be, Si, B, could compete (but raise other design issues).

Carbon nanotube ropes *may* outperform C-fibre, but performance data vary widely.

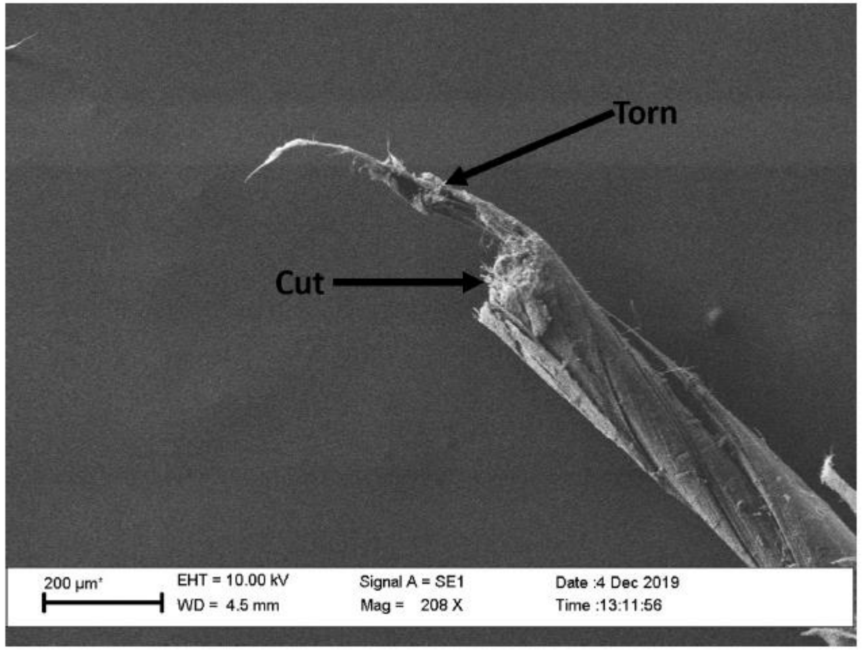
# **Part II:** Investigating CNT ropes*

Material Merit Index: $$c_p T_{max} \left( \frac{\sigma_f}{\rho} \right)^{\frac{1}{2}}$$

Aims: Compare CNT rope to available Carbon fibres (all material samples from CERN)




(a) Carbon Fibre: 7.5 µm Diameter

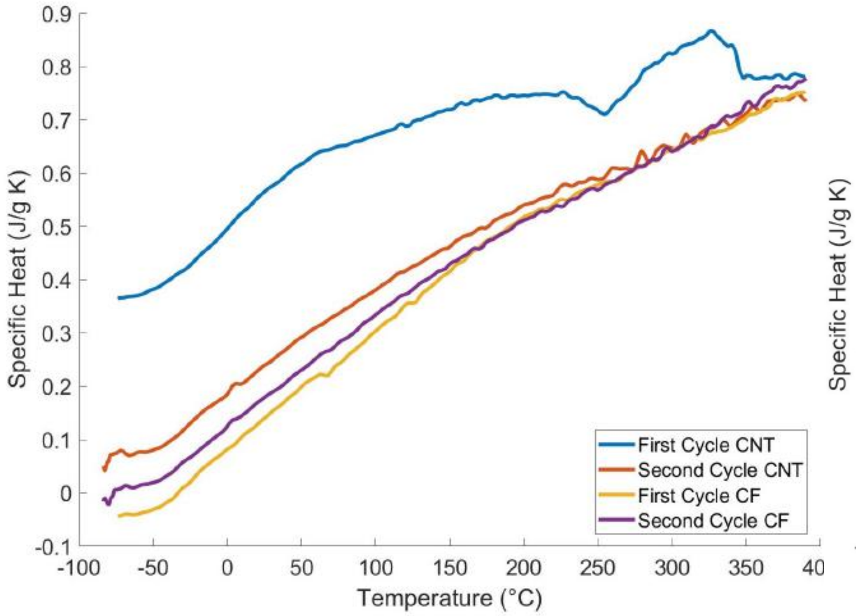


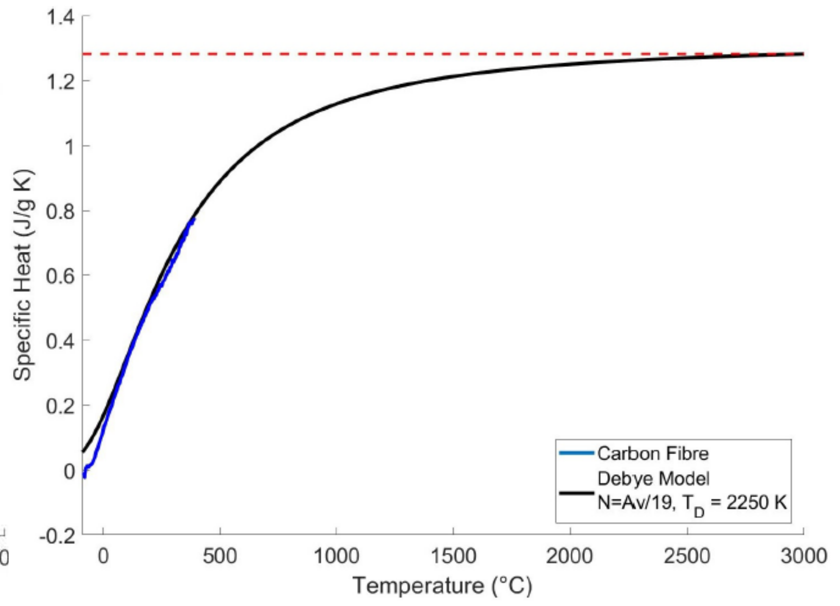

(b) CNT rope: 100 µm Diameter

*Acknowledgement: Ben Barclay, MEng Project Report, University of Oxford

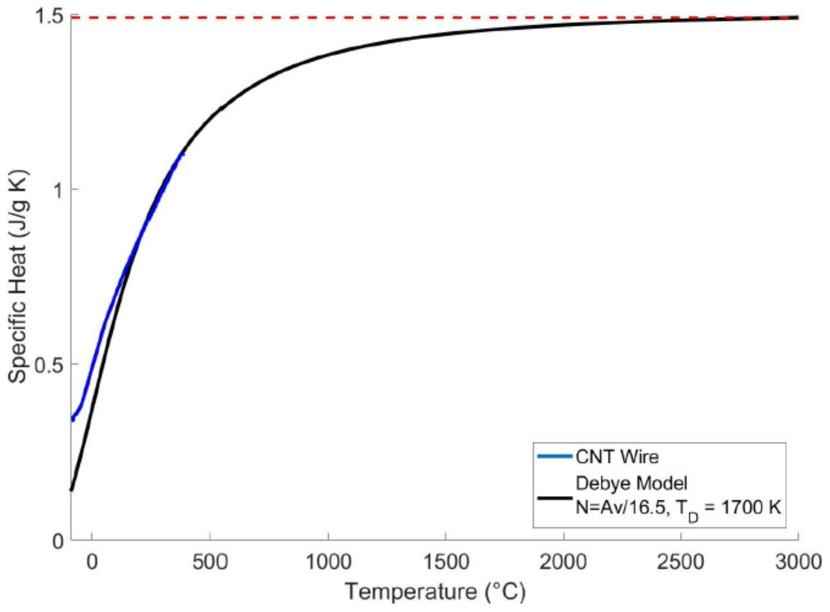
# Comparing CNT thermal properties to C-fibre

Differential Scanning Calorimetry:




(a) Carbon Fibre




(b) Carbon Nanotube Wire

Our measurements indicated the CNT had $c_p$ slightly greater than C-fibre at low temperature. In our system we were limited to < 700K.

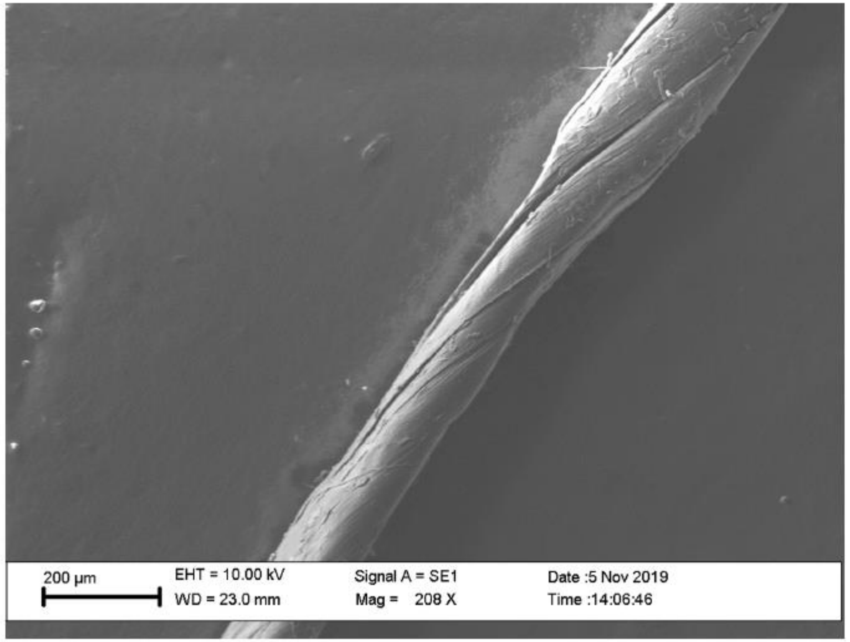
Sublimation temperature $T_{max}$ was not tested, but expected to be similar to C-fibre

# Comparing CNT mechanical properties to C-fibre

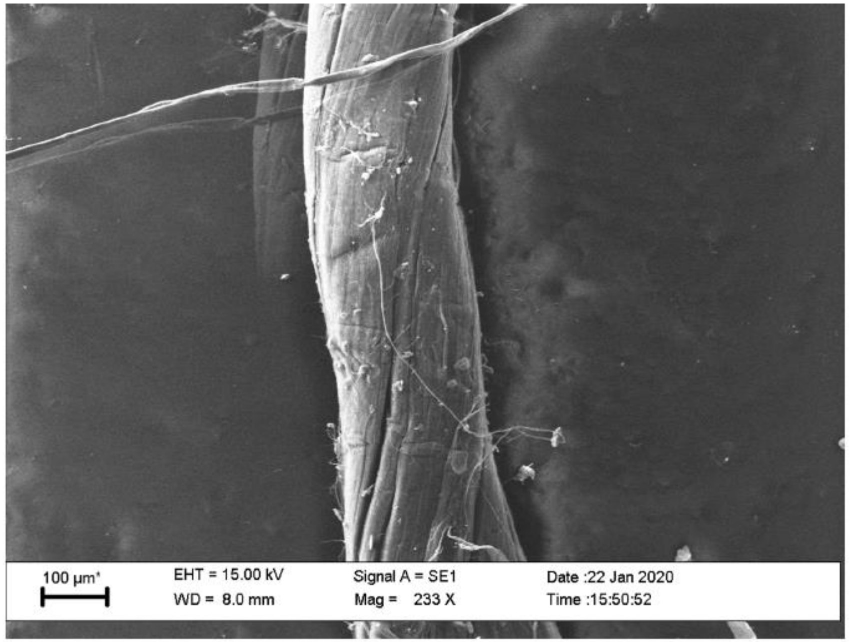
Density measurements: (mass/unit length)

- by weighing individual lengths of fibre
- “density” results variable due to range of fibre diameter
- note $\sigma_f/\rho$ is equivalent to *breaking force/mass per unit length*

Diameter variation in CNT-rope (nominal 100μm)



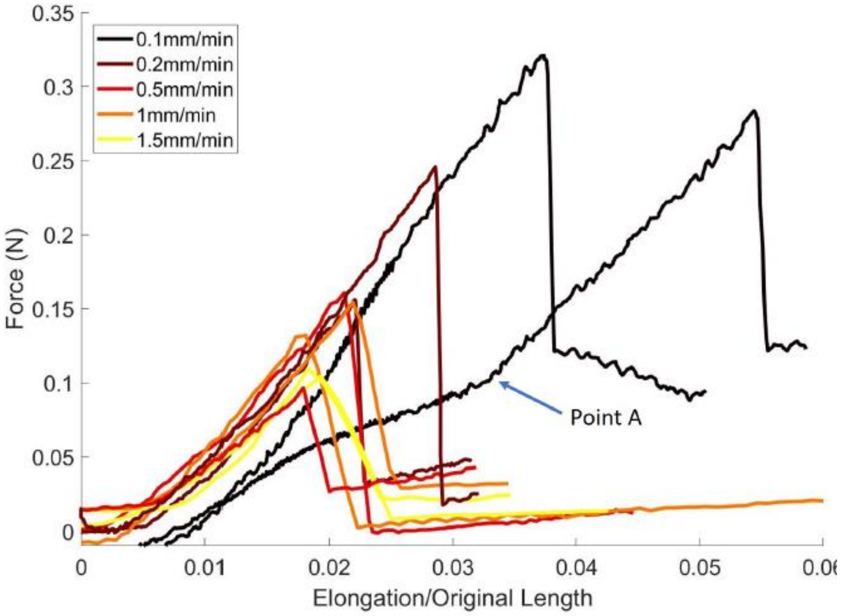

(a) 125 μm Diameter



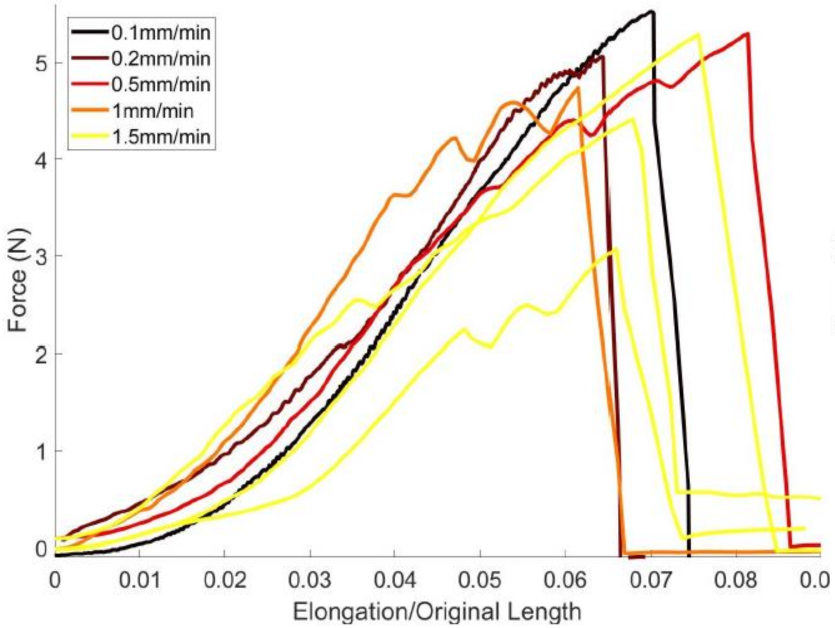

(b) 253 μm Diameter

# Comparing CNT mechanical properties to C-fibre

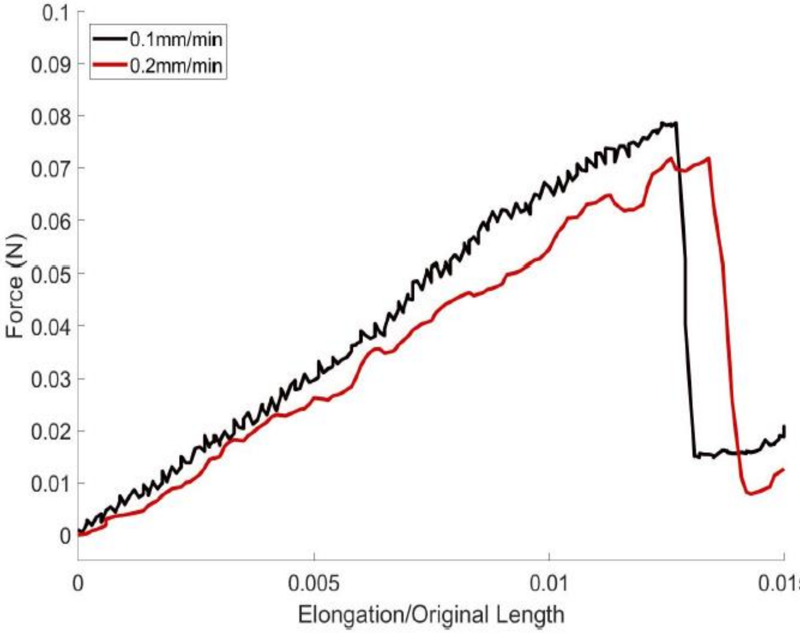
## C-fibre 7µm (2-5GPa)




## CNT rope 100µm (0.5-0.7GPa)




## CNT rope 10µm (1.4-1.8GPa)



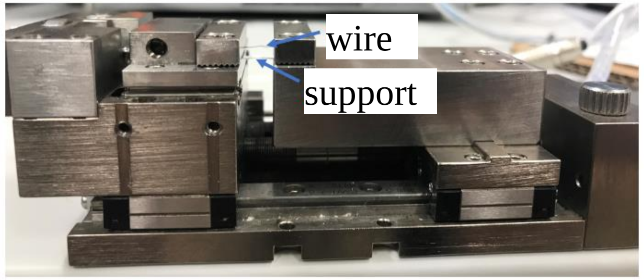




Figure 5.3: Side View of Deben Stage with Clamped Sample Holder

- C-fibre shows greater strength variation
- 100µm CNT rope shows a gradual stiffening response
- finer fibres typically show greater $\sigma_f$

# CNT rope materials in the Ashby plot

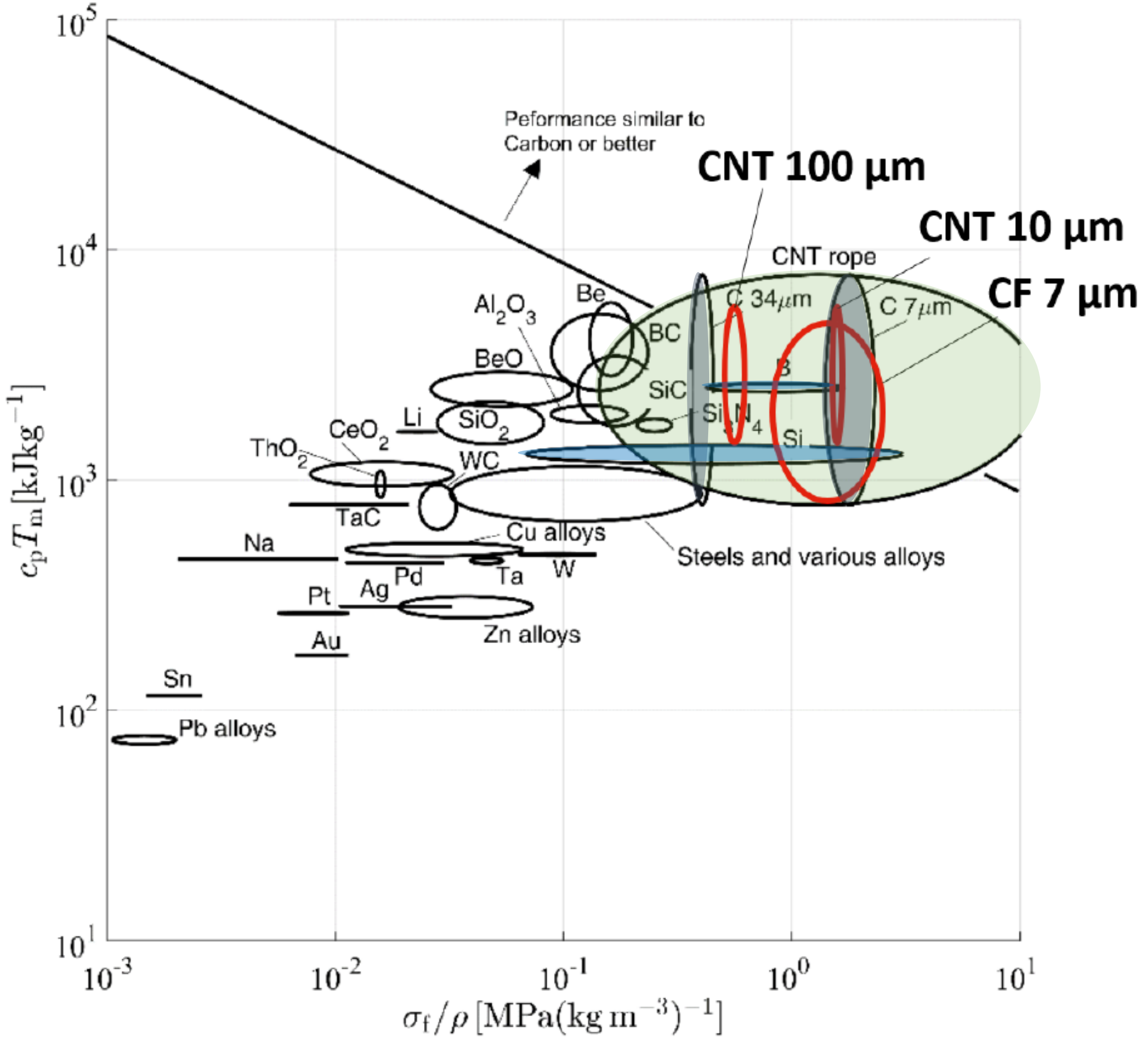
Observations:

Finer fibres generally give improved mechanical performance (size effect).

At the same fibre thickness, CNT rope generally gives better strength than C-fibre.

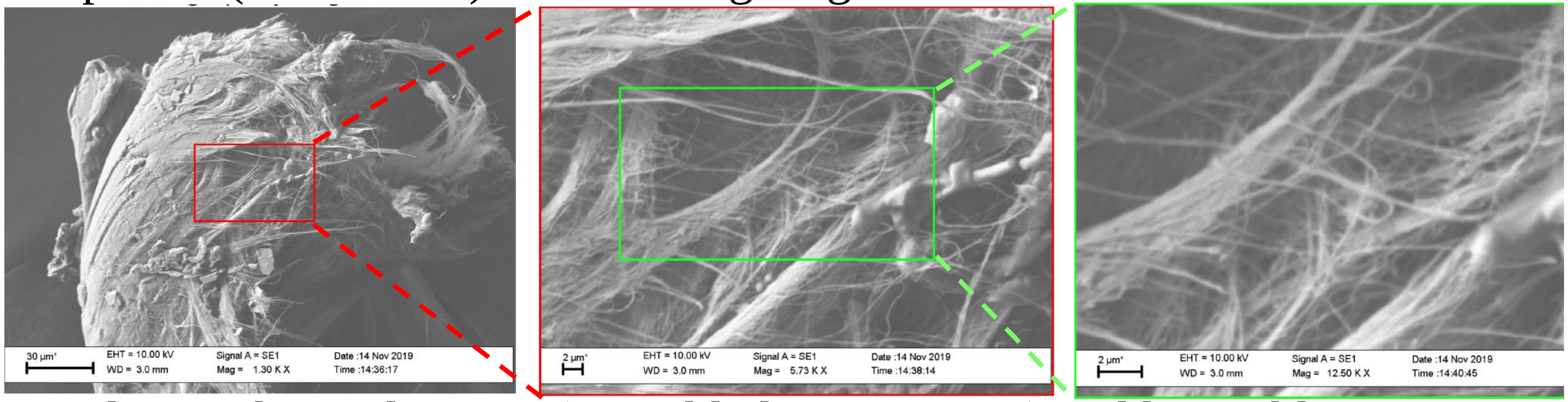
The improvements in switching from C-fibre to CNT rope are likely to be relatively small.

CNT ropes may have less scatter in strength (more consistent).

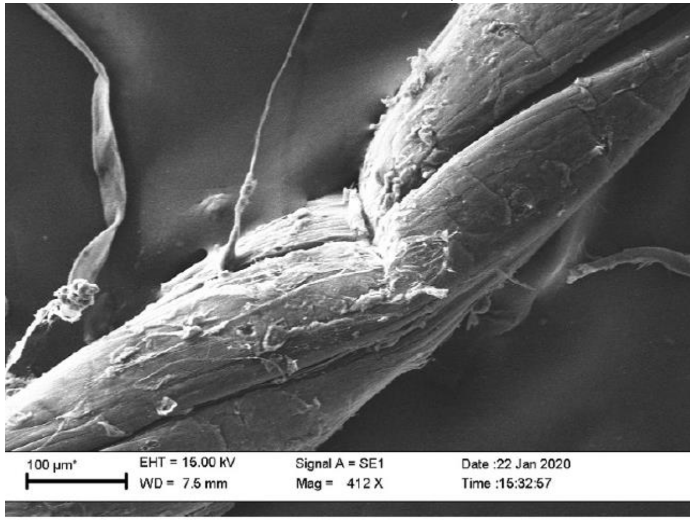


# Damage tolerance in CNT rope materials

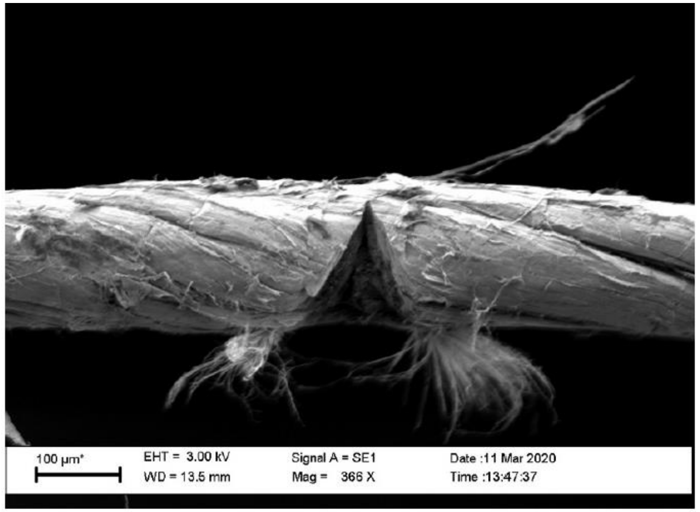
CNT rope end (as received) at increasing magnifications




Damage by mechanical means (razor blade impression) and laser ablation:

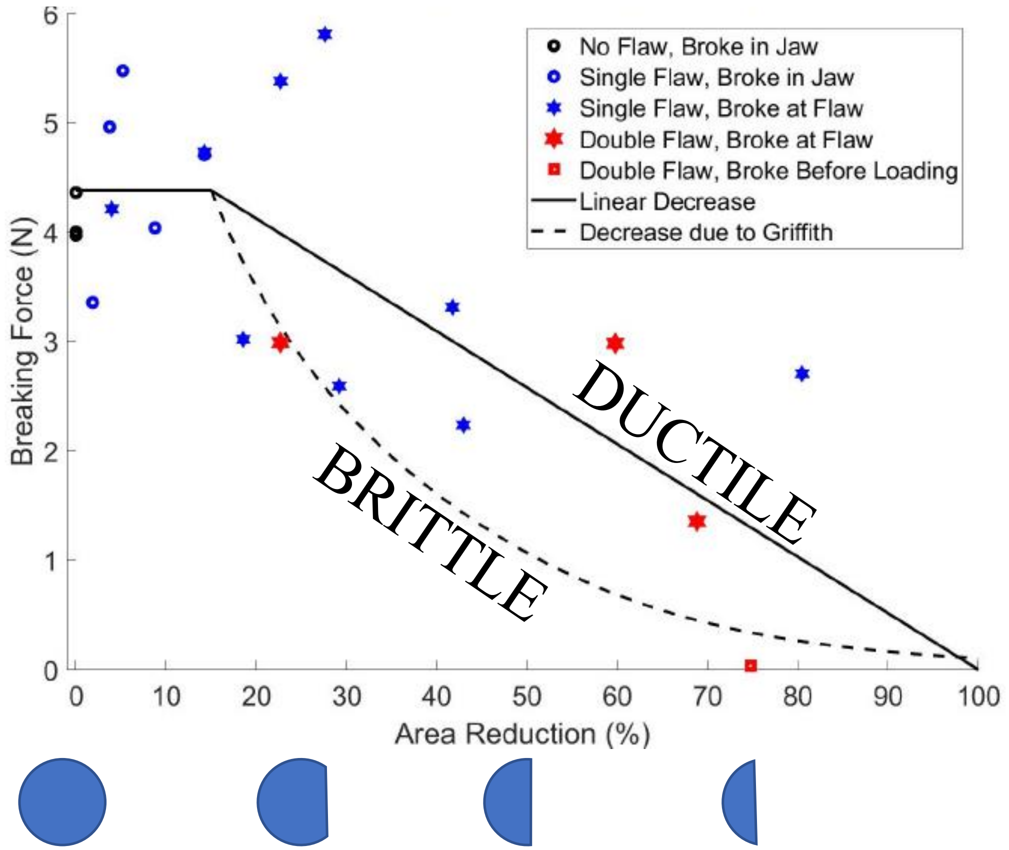



(b) Flaw by Razor Compression

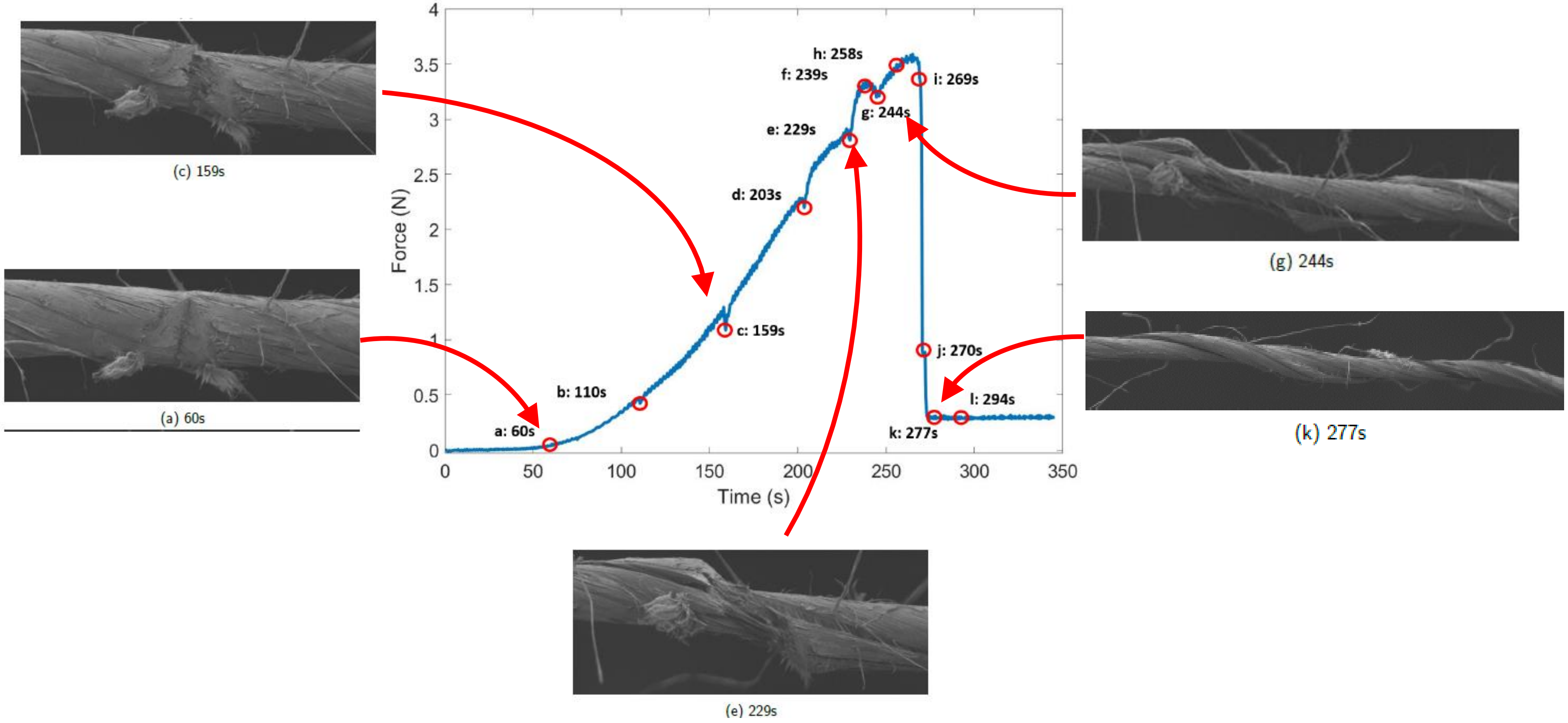



(a) Flaw by Laser Ablation

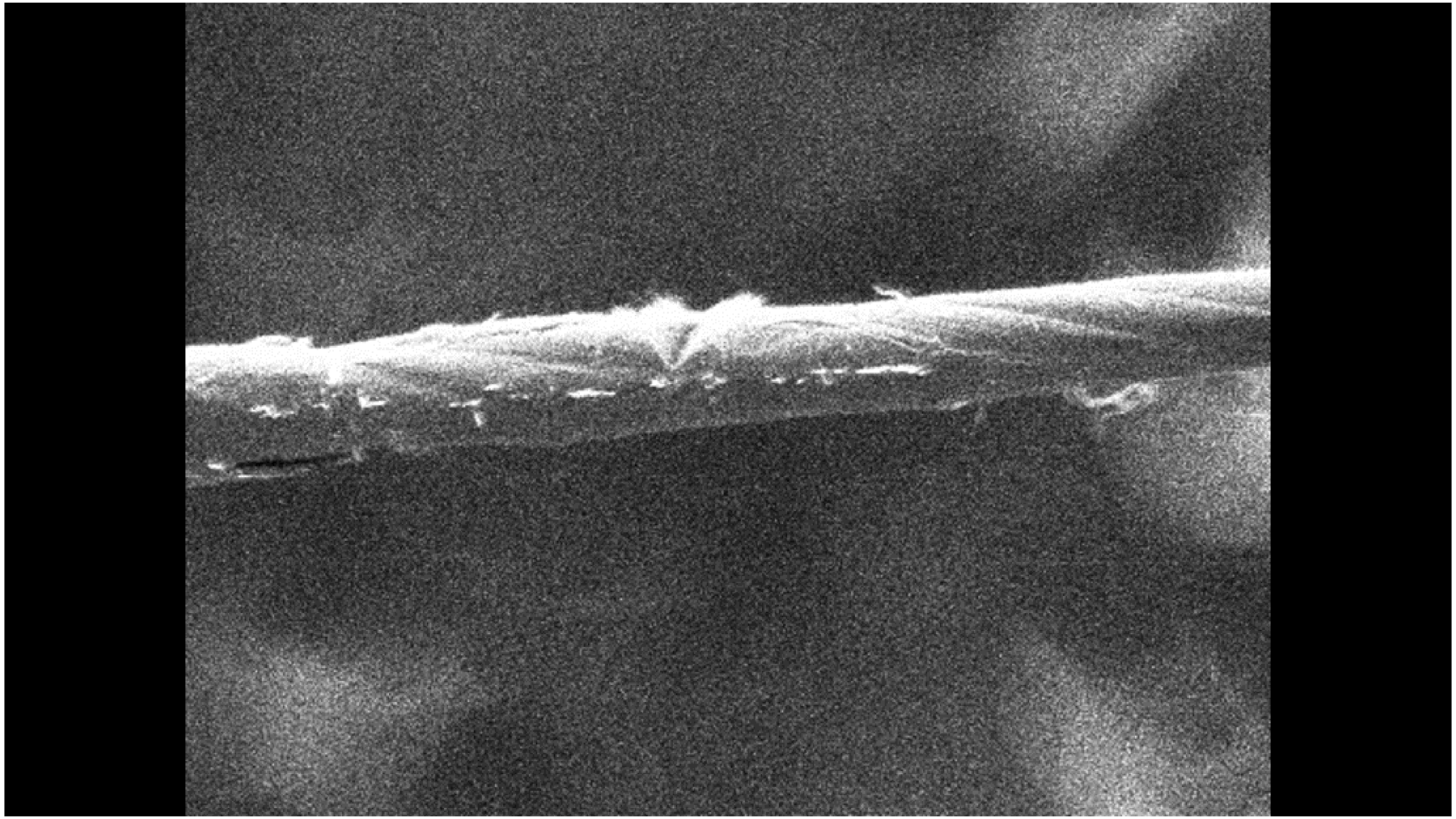
# Damage tolerance in CNT rope materials



# CNT rope materials – unravelling failure in SEM



# Ablated 100μm CNT rope – failure in SEM



# Conclusion

Analysis using the Ashby materials selection method confirms Carbon as a high-performing material for the wire, and identifies some alternatives.

Carbon nanotube (CNT) ropes offer comparable performance to carbon fibres, with potential for damage tolerance and improved reliability.

Some scanner design parameters may also contribute – in particular scan speed, coupled to wire length (shorter is better) and scanner arm length (longer being better subject to adequate stiffness).