The Strategic University Steel Technology and Innovation Network Presents

Task 6: Thermal Efficiency

Cameron Pleydell-Pearce

SUSTAIN

Future Steel Manufacturing Research Hub

UKRI Engineering and Physical Sciences Research Council

Swansea University Prifysgol Abertawe

Names and Organisations

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- Ria Mitchell (PDRA) Material Characterisation
- Michael Dowd (PDRA) High Temperature Testing
- Karen Perkins (As. Prof) High Temperature Testing
- Matt Burton (PDRA)* Thermo-electric generators
- Matt Carnie (As. Prof) Thermo-electric generators
- Geraint Howells (PhD) Thermo-electric generators

Liam Cotton (TATA Steel), Ebrima Sallah (PhD), Taco Jansen (MSc), Dr Jon Willmott

Introduction: Environment

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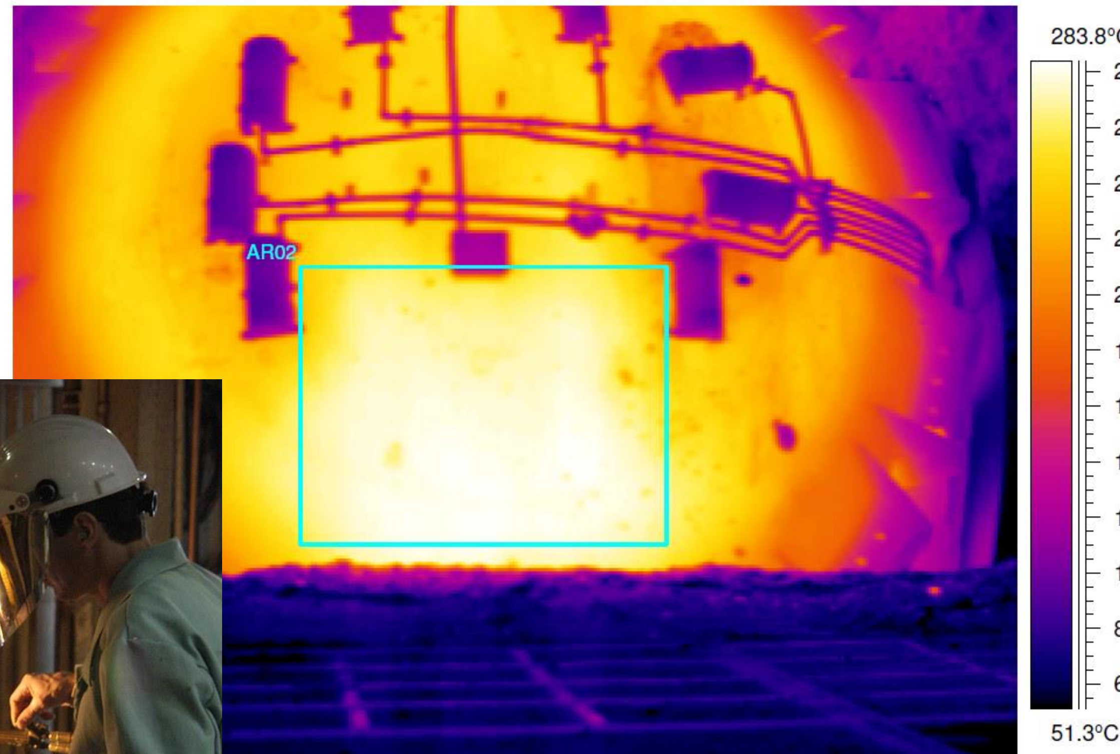
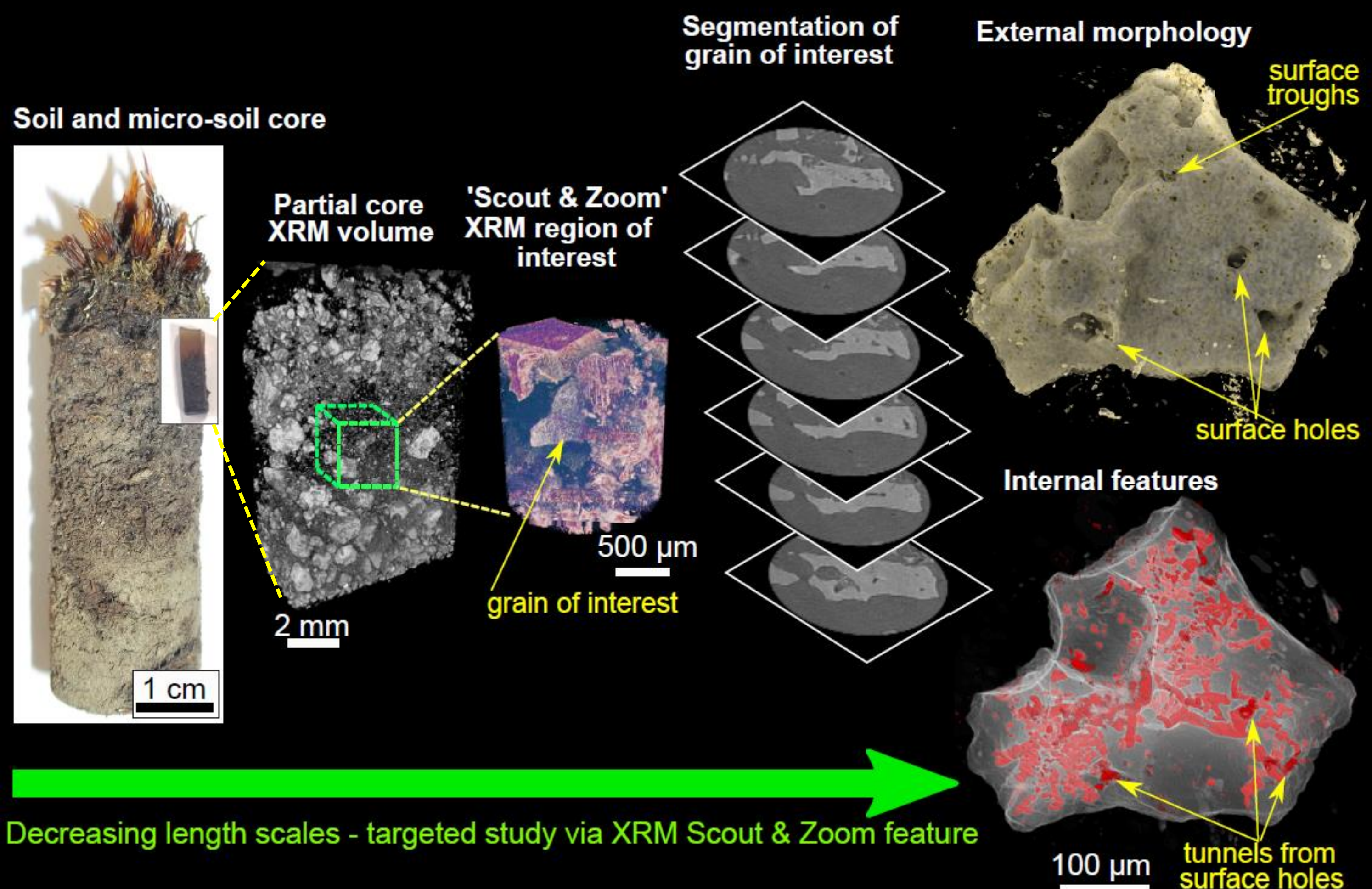


Introduction: Approach



Mitchell et al., 2018, Micro. & Microan;
Mitchell et al., in prep. (Scientific Reports, EarthArXiv)

Introduction: TEGs

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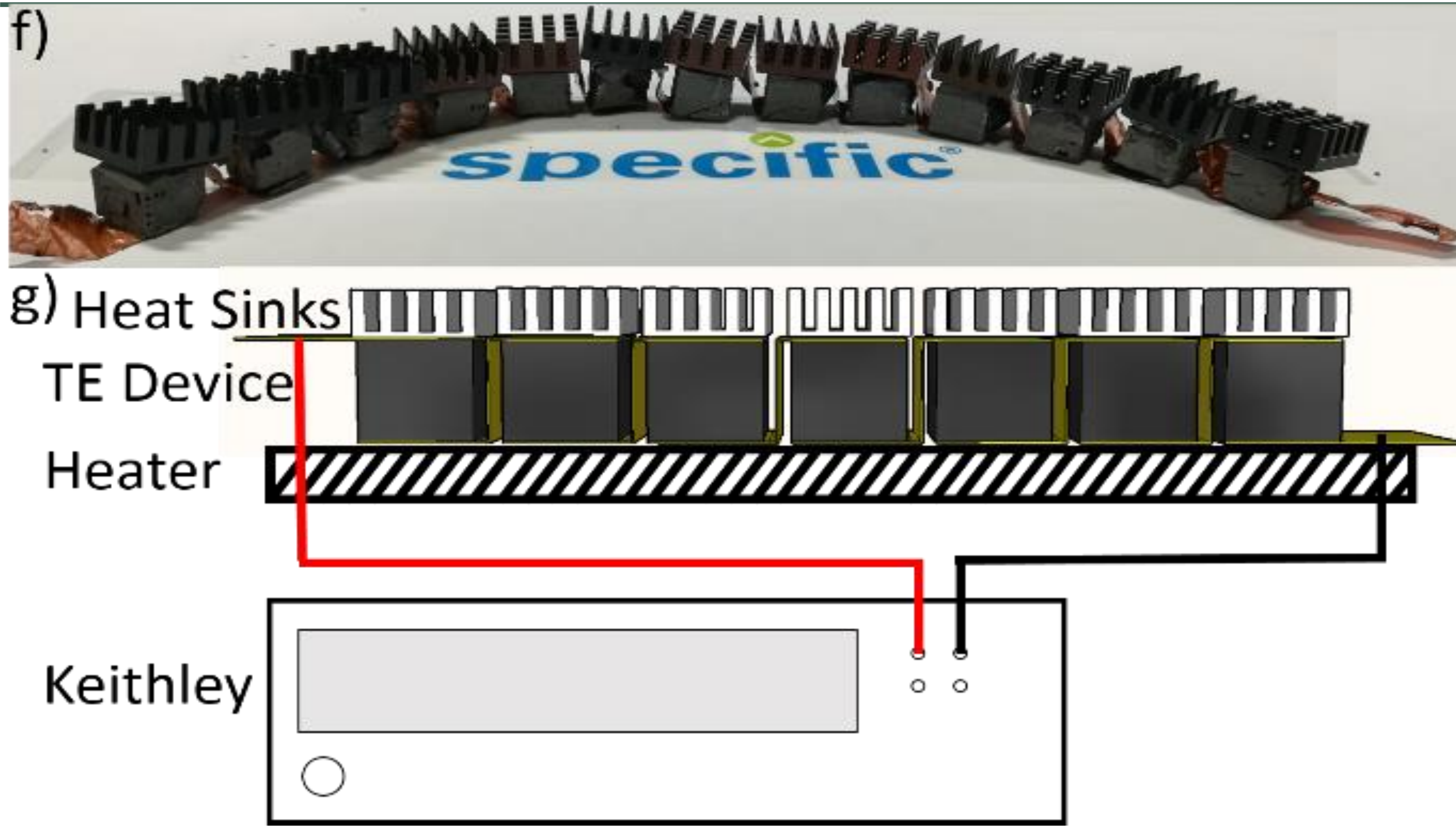

Carnie & Burton *et al* Adv. Energy Mater. 2019, 9, 1900201

Aims and Impact

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Aims

- Develop as multiscale ex-situ structural characterisation approach for refractories.
- Improve understanding of structure-property relations in magnesia carbon refractories.
- Develop robust, cost effective thermoelectric materials / devices for integration into refractory linings.
- Build UK academic skill base in the field of refractories.

Impact

This activity has the potential to significantly improve value in use and recycling of refractories and introduce greater online diagnostic capability with the potential to deliver multi £m annual savings for any one steel making company.

Links

T5 – Thermal Modelling of Ladles

T8 – Sensors

Progress: Furnace Set-Up

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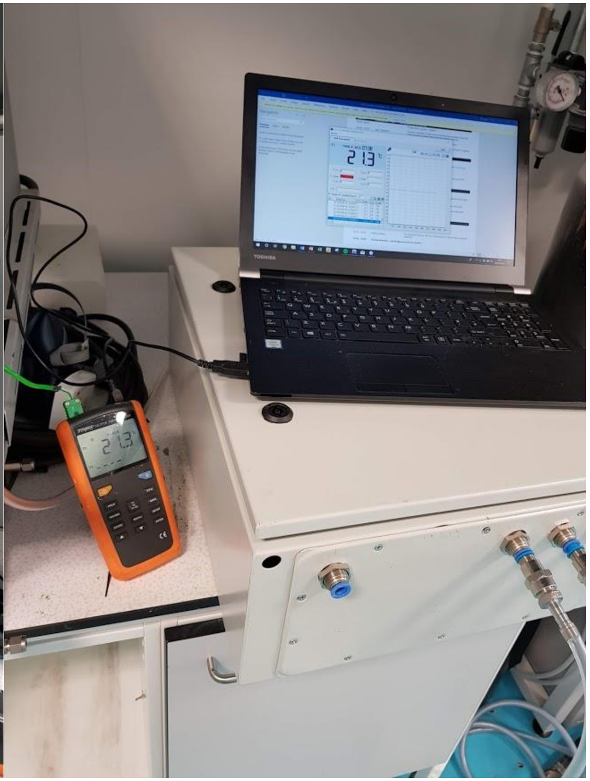

Progress: Furnace Set-Up

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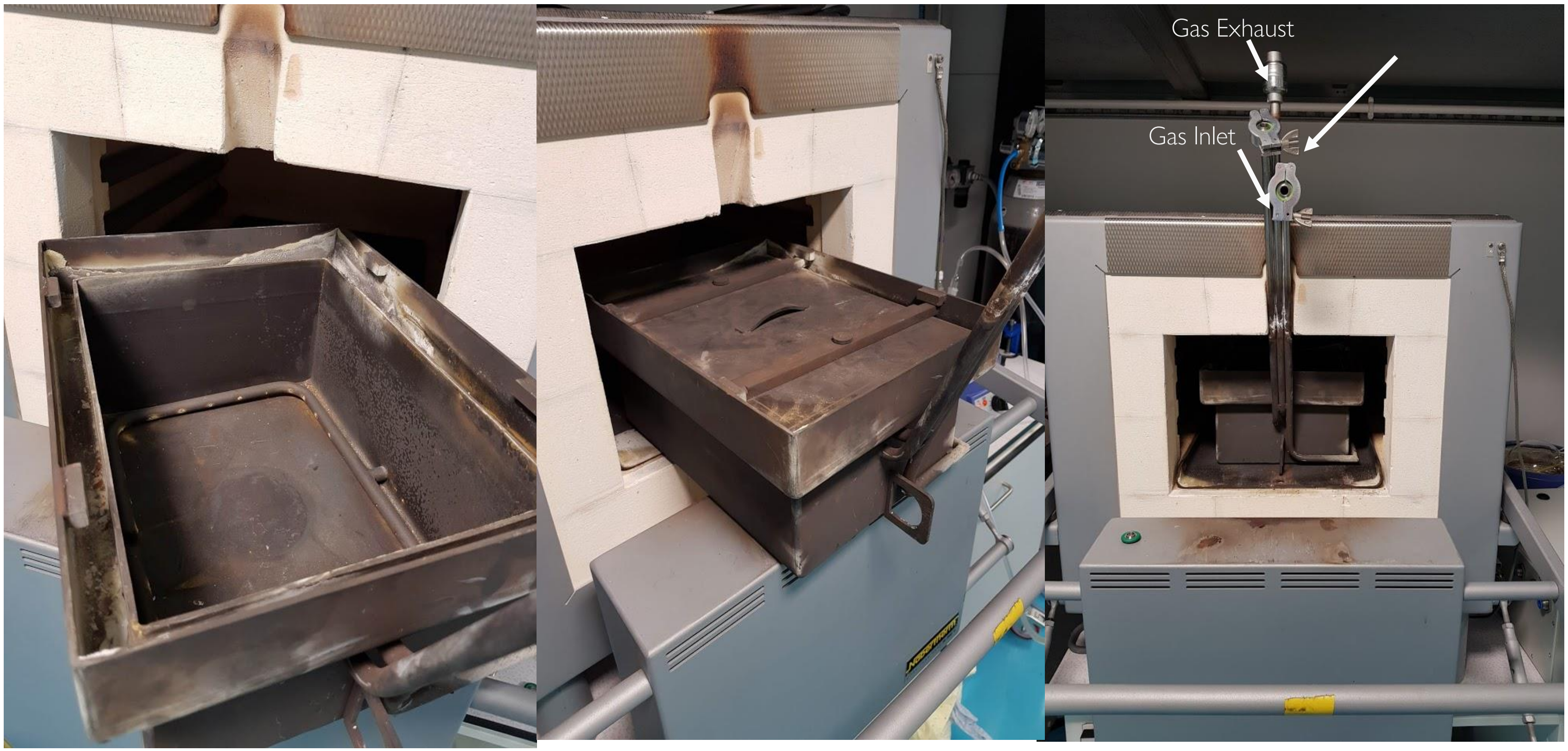
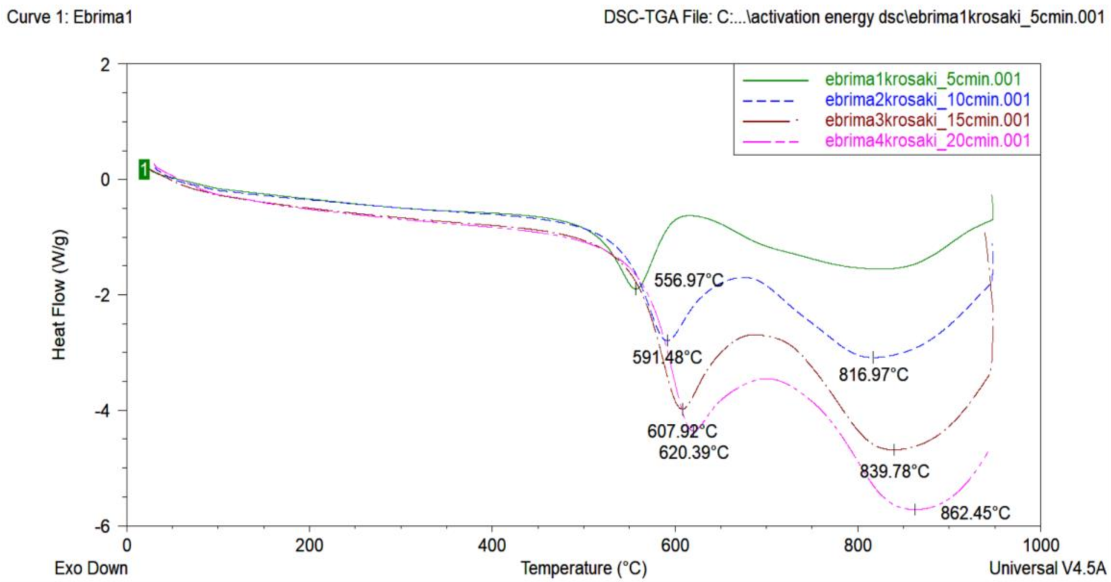
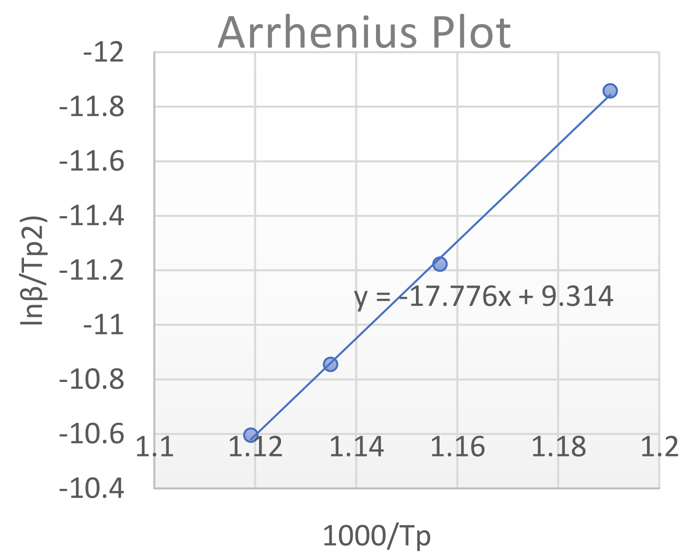


Progress: Material Testing





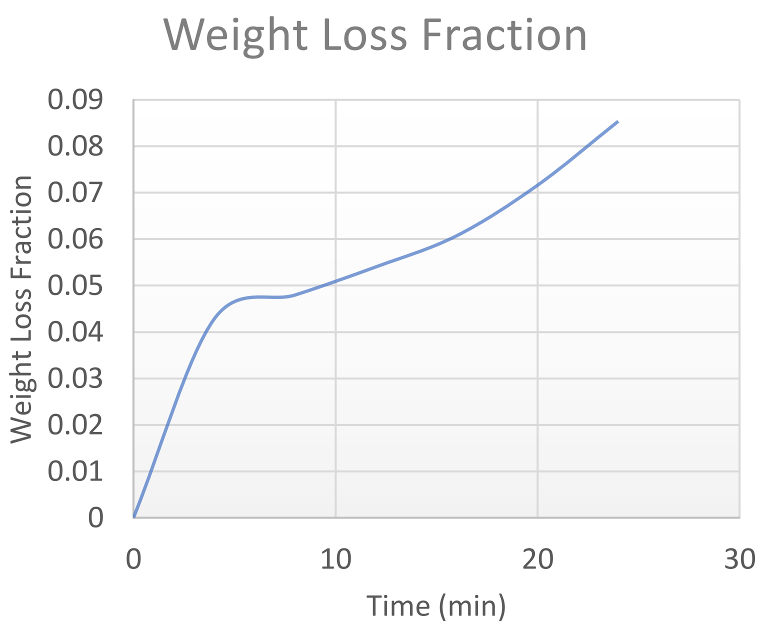
Plot based on the Kissinger Non-Isothermal Method of calculating Ea and A

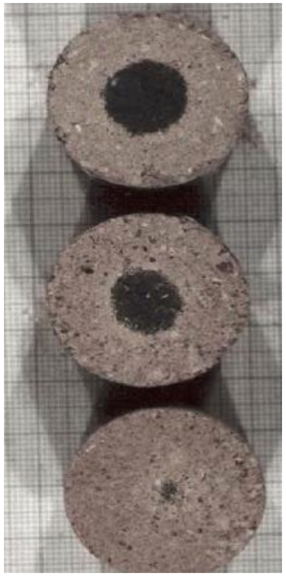
$$K = A\,exp\left(\frac{-Ea}{R\,T}\right)$$

Ea -147719 J/mol

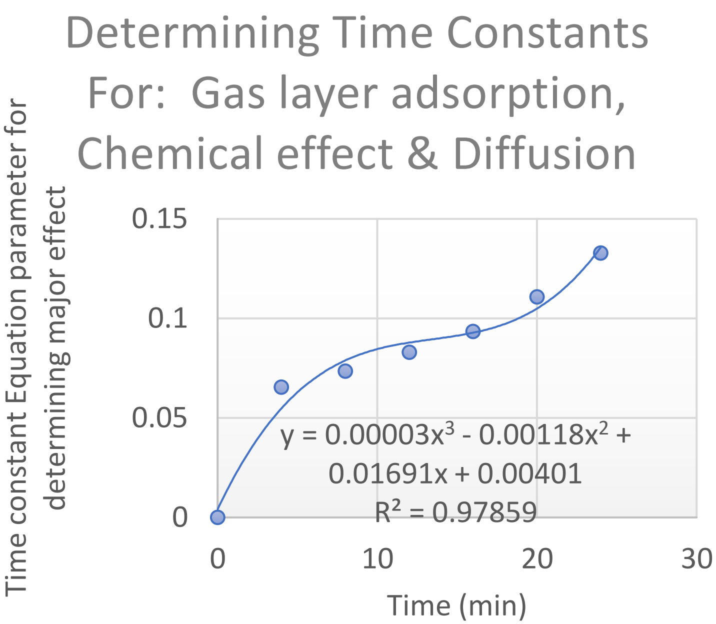
$$ln\left(\frac{\beta}{Tp2}\right) = ln\left(\frac{A\,R}{Ea}\right) - \frac{Ea}{R\,T}$$

Progress: Material Testing





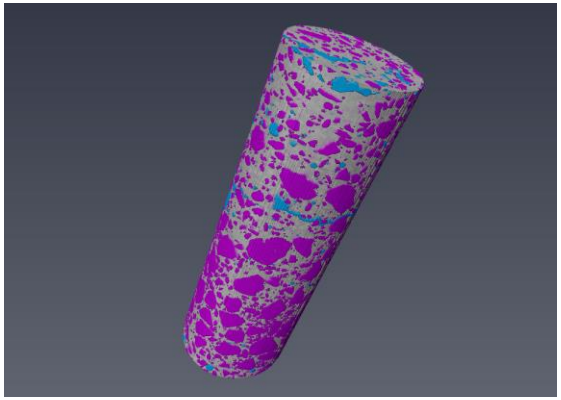
B. Hashemi et al. (2006), Effects of resin and graphite content on density and oxidation behaviour of MgO-C refractory bricks. Ceramics International , 32, 313–319

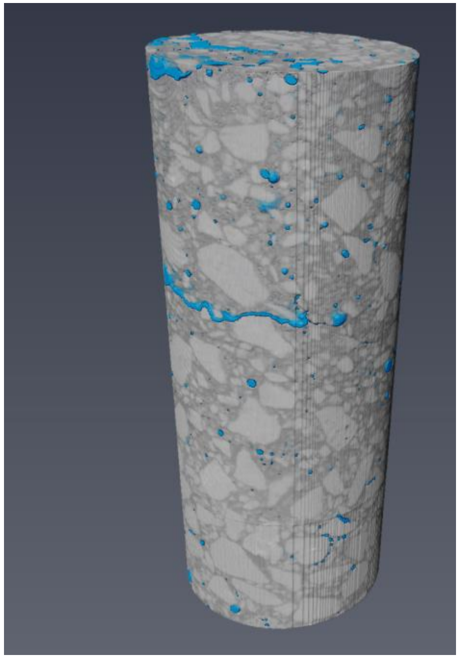


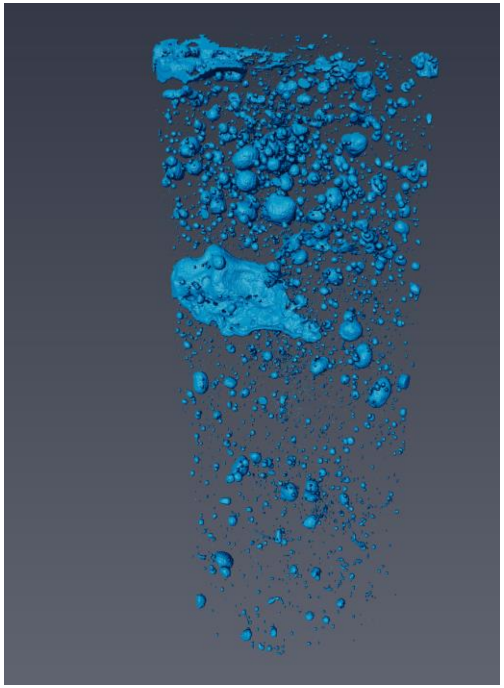
$$t = \frac{\rho_{Gm} R}{2[O_2]} \left\{ \frac{X}{2K_g} + \frac{R}{4D_e}[X + (1-X)\ln(1-X)] + \frac{1}{K_{ch}}[1-(1-X)^{1/2}] \right\}$$

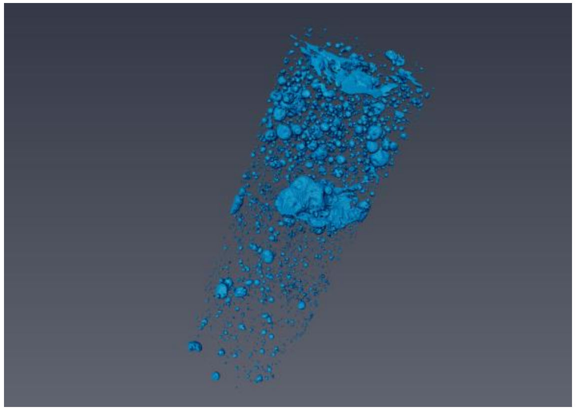
Progress: XCT of Refractories

Porosity (Macro)

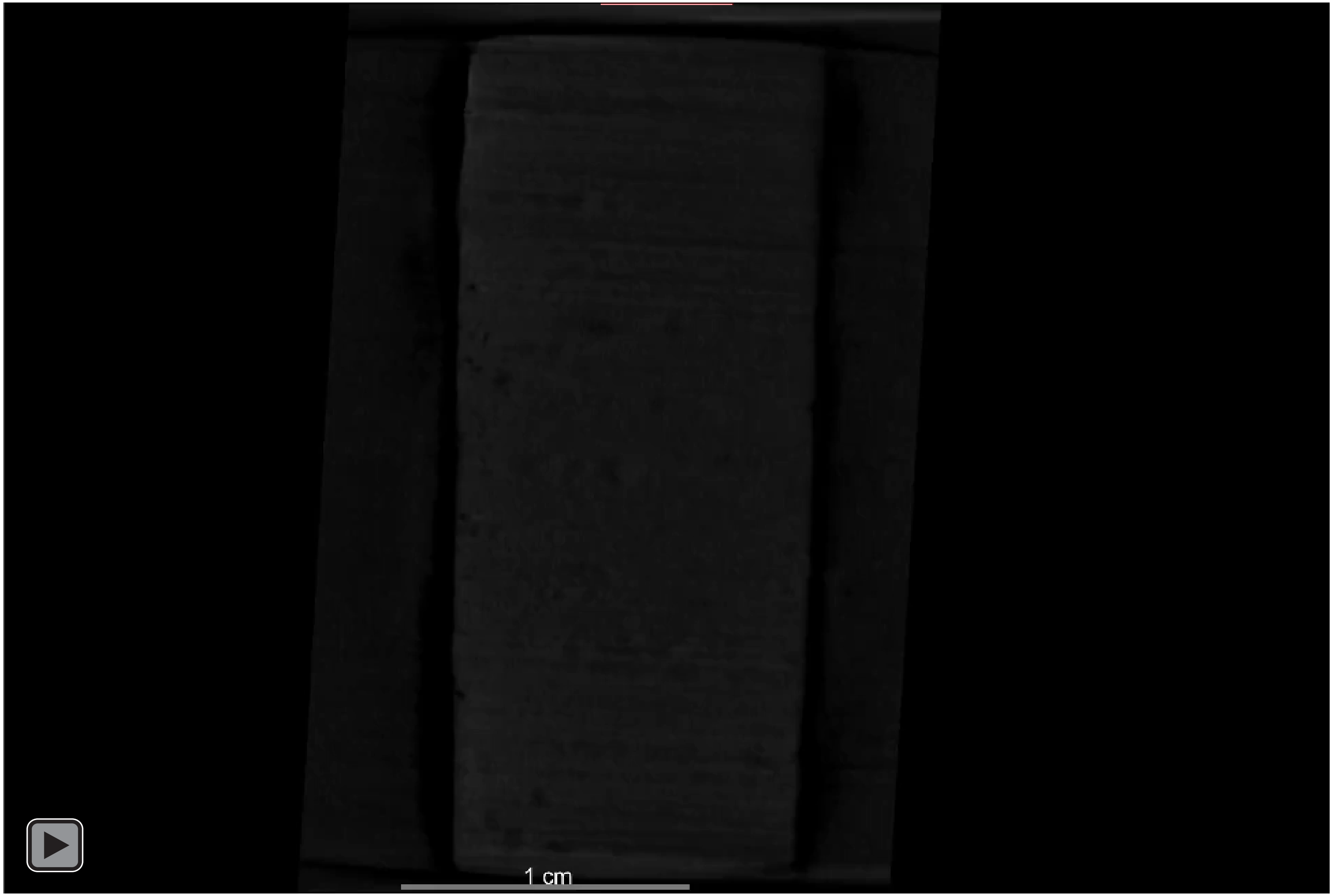




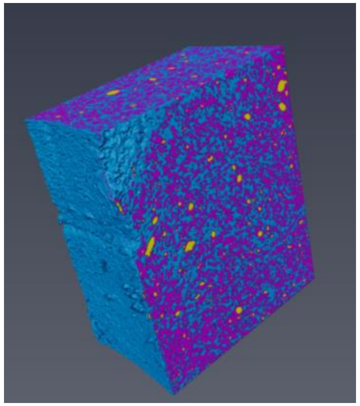




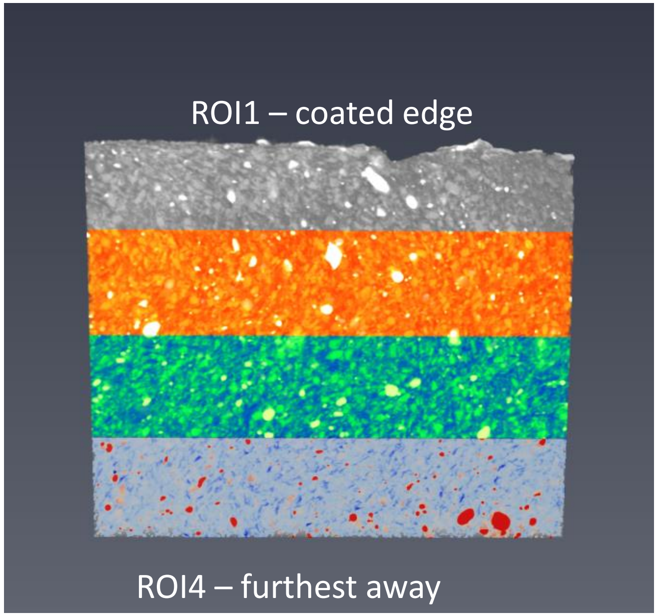
Progress: XCT of Refractories



Progress: XCT of Refractories

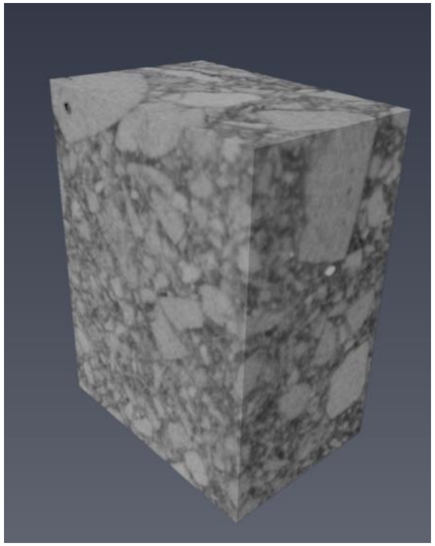


Component	%
High density grains	23
Low density grains	37
Matrix/binder	39

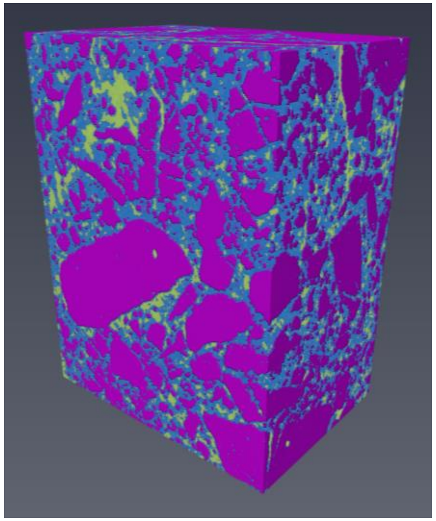


COMPONENT	ROI 1 (coating)	ROI 2	Roi 3	ROI 4 (furthest away)
High density grains	24.7	22.9	22.4	23.1
Low density grains	37.0	36.4	36.5	39.4
Matrix/binder	38	40.7	41.1	37.3

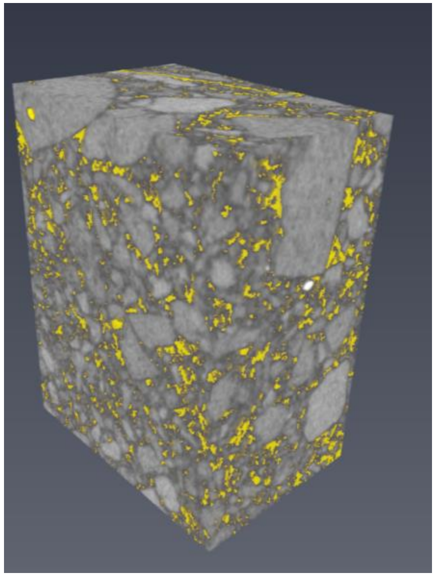
Progress: XCT of Refractories



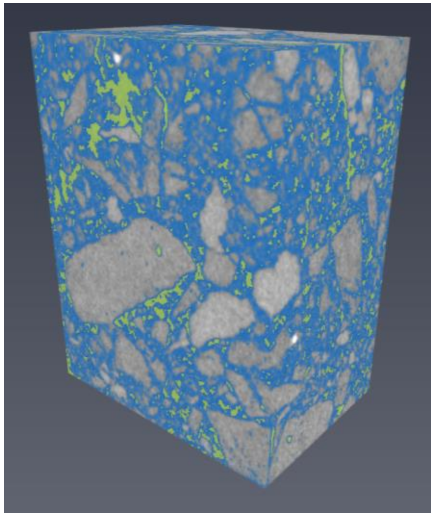
Whole core



Pink = grains
Blue = all matrix
Yellow = darker areas of matrix – carbon?



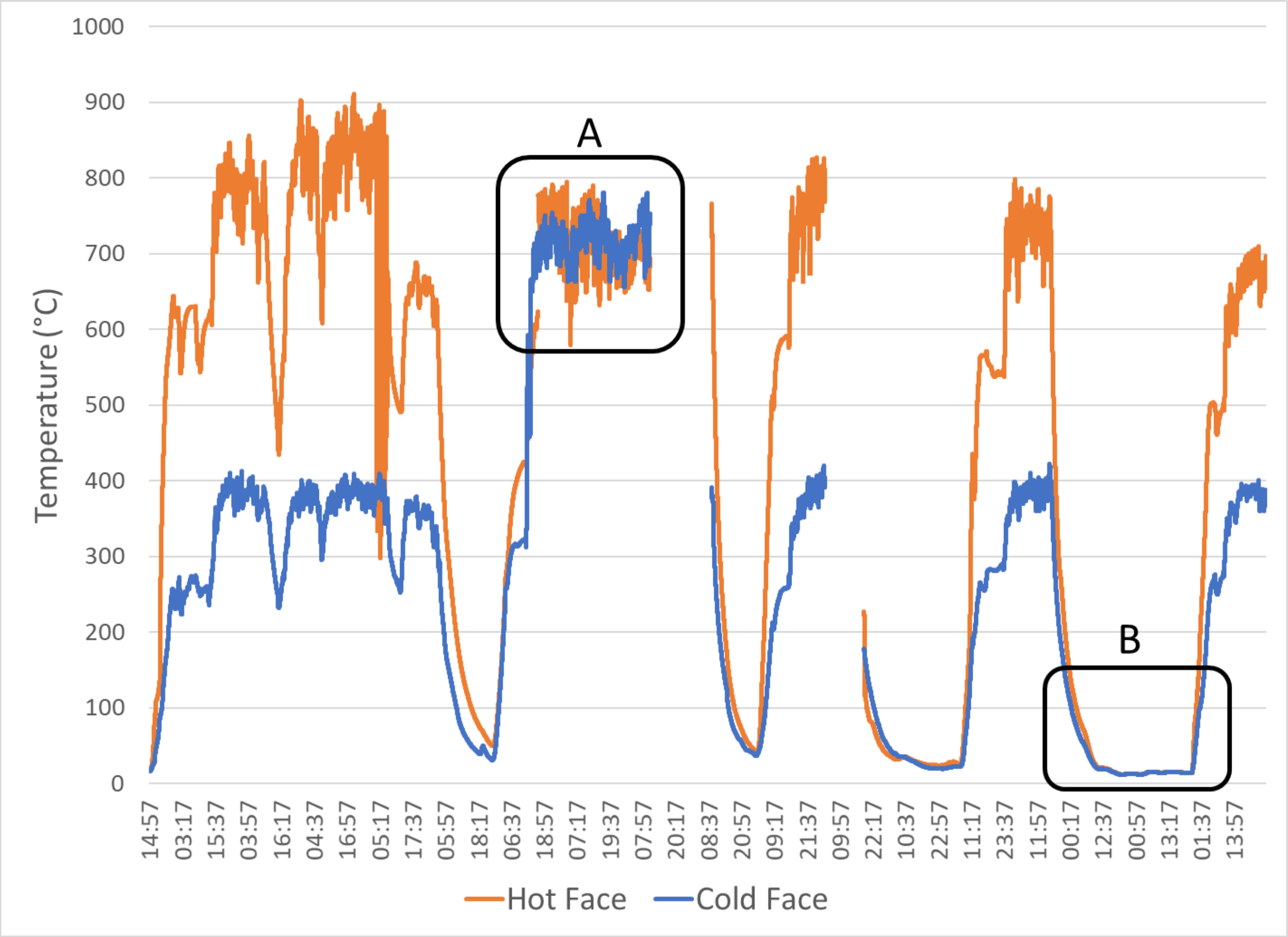
Areas of carbon(?)



Matrix + darker areas (carbon?)

Sub core - ~1.5mm^3

Progress: Ladle Conditions



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Thermal Efficiency: Thermoelectrics

Matthew Burton, Swansea University

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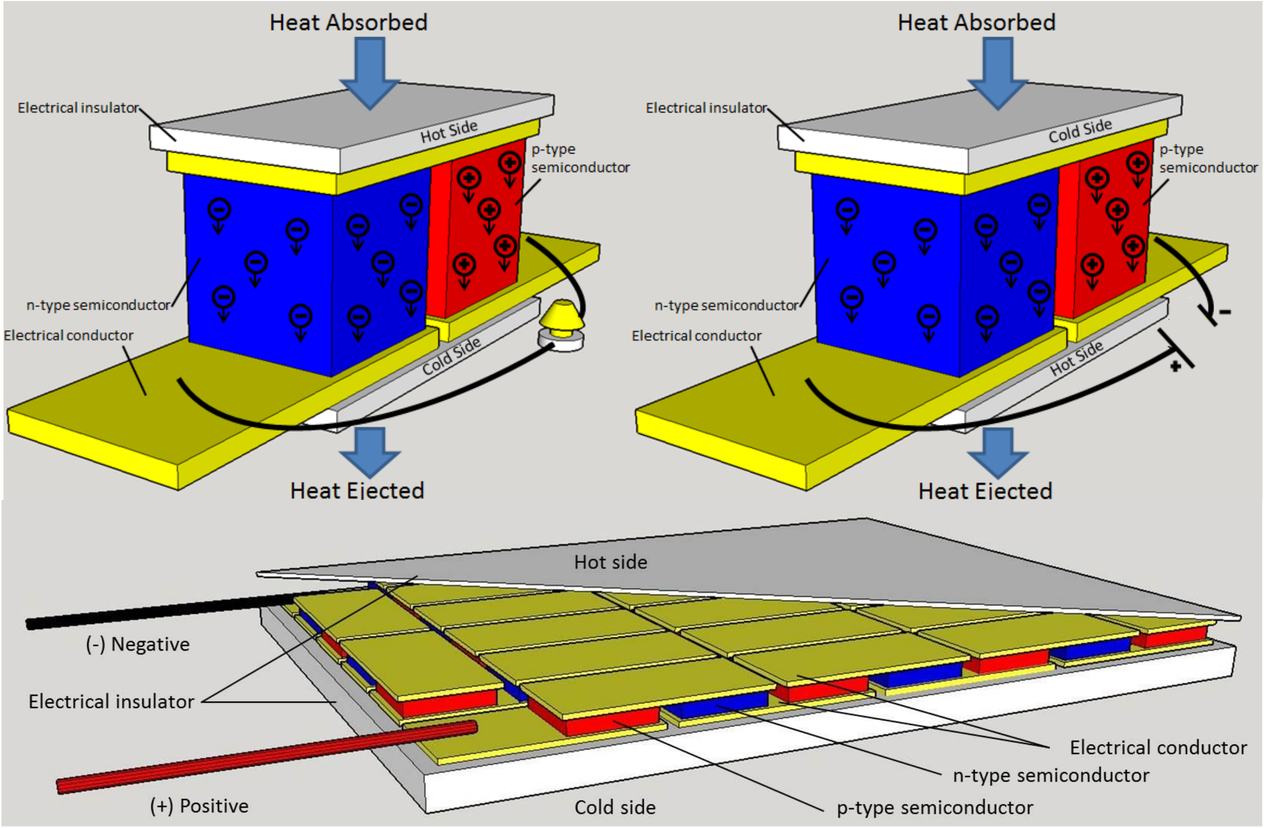
Thermoelectrics: How do they work?



- Place a temperature gradient over a p and a n leg
- Causes diffusion of charge carriers (electrons or holes) through the legs from the warmer side to the cooler side resulting in a voltage
- Completed circuit allows current to flow
- Can be run in reverse
- In practise several pairs of legs needed to produce sensible voltage

Printed Thermoelectrics For Bespoke Generators

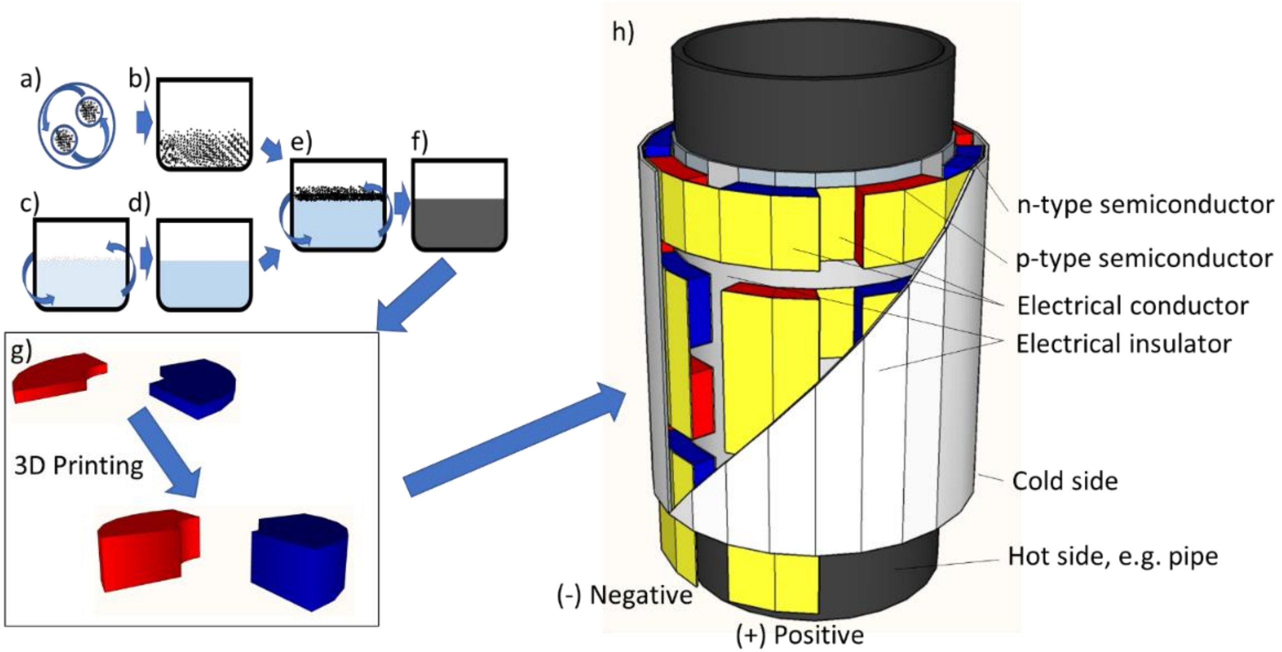


Figure 1 – Schematic illustration of printed thermoelectric generators: a) ball milling powders, b) resulting powders, c) water and binder mixing, d) resulting mixture, e) mixing ball milled powder and binder mixture, f) resulting ink, g) 3D printing bespoke thermoelectric elements, h) completed thermoelectric device on a curved surface, e.g. pipe.

- Printed thermoelectrics can be used in steel works to harness waste heat energy and make self powered sensors or even generators
- Key target of a 'Smart Ladle', a ladle that uses a thermoelectric generator as a self powered thermometer
- Other areas for sensors and energy harvesting potential should be looked into.

Efficiency/Important Material Properties

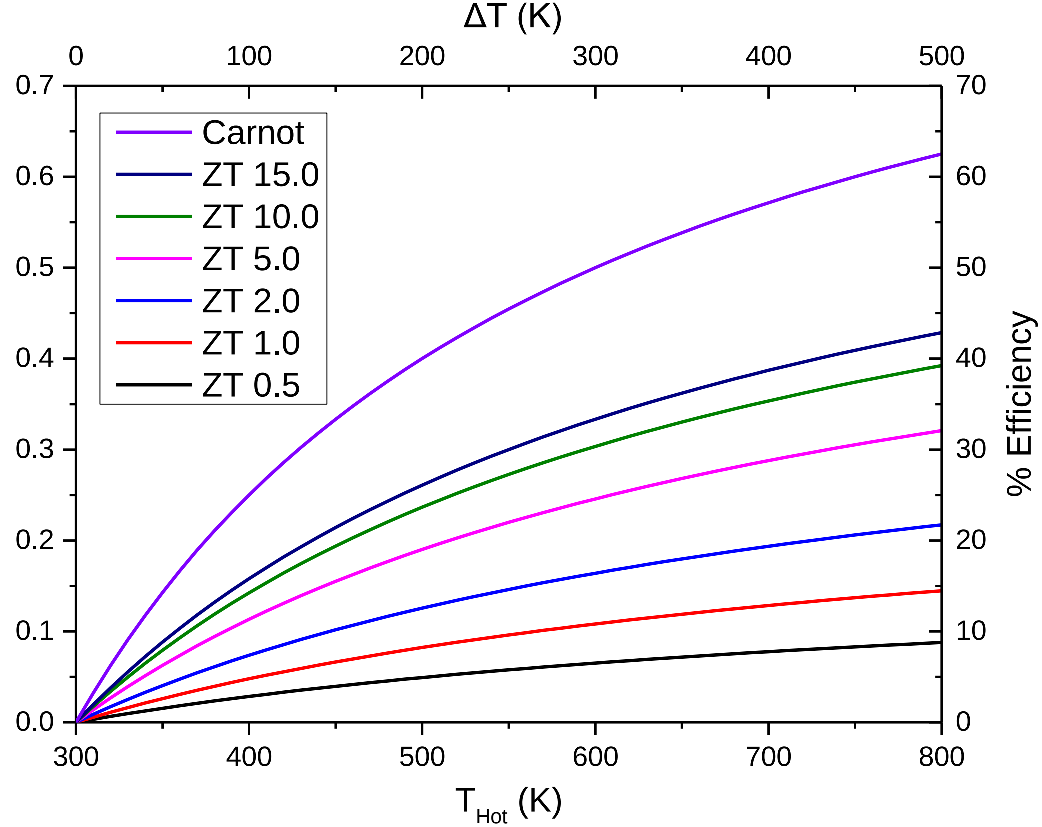
$$\eta = \frac{T_H - T_C}{T_H}$$ (Carnot efficiency limited)

$$\eta_{max} = \frac{T_H - T_C}{T_H}\frac{\sqrt{1+Z\bar{\bar{T}}}-1}{\sqrt{1+Z\bar{\bar{T}}}+\frac{T_C}{T_H}}$$ (Also material limited)

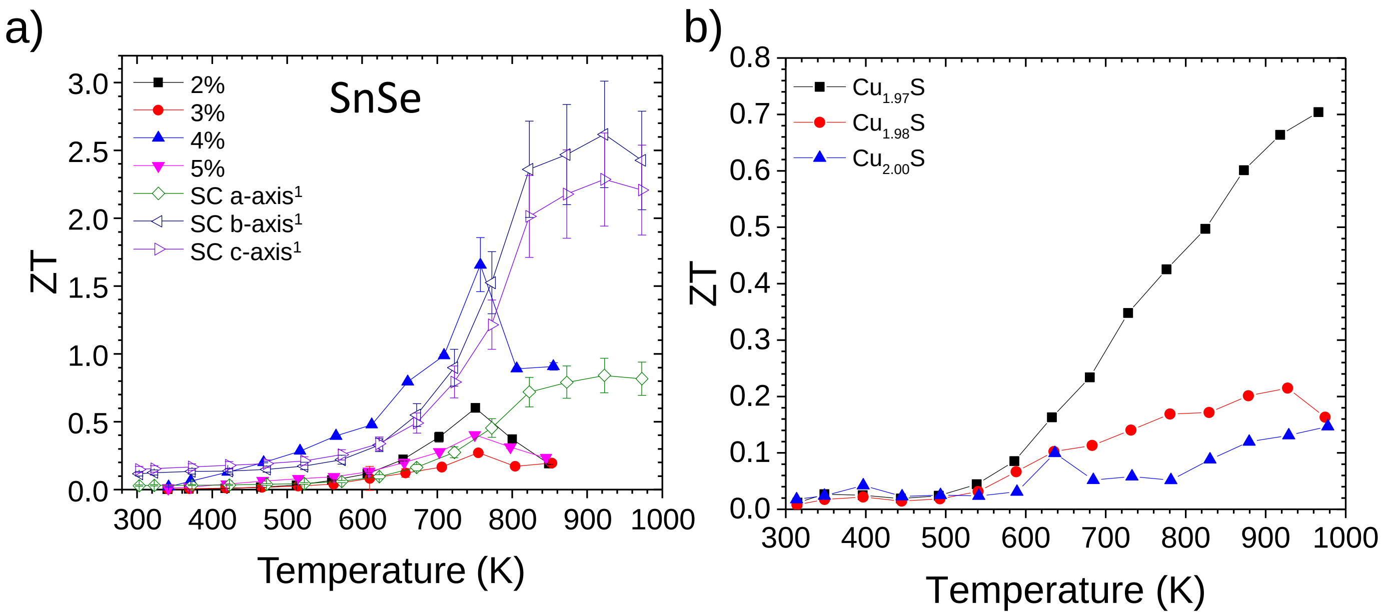
$$Z\bar{\bar{T}} = \frac{\left(S_p - S_n\right)^2 \bar{\bar{T}}}{\left(\sqrt{\rho_n \kappa_n} + \sqrt{\rho_p \kappa_p}\right)^2}$$

$$ZT = \frac{S^2\sigma}{\kappa}T$$

$$PF = S^2\sigma$$



How Well Do Printed Thermoelectrics Perform



- Very very rough calculation suggests a small (~5 cm^2) optimised printed thermoelectric generator device from these materials can generate in the order of 1 W on a ladle
- The aim would be to use this power to make a wireless self powered sensor
- Many hurdles to overcome, not least getting a stable n-type material and contact resistance issues
- Very early and extremely crude test device only produced 20 μW

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