Engineering performance of thermoelectrics for space radioisotope power systems

Hugo Williams

Ramy Mesalam

Richard Ambrosi

hugo.williams@le.ac.uk

@DrHRWilliams

Acknowledgements

Emily Jane Watkinson, Jon Sykes, Tony Crawford, Alessandra Barco
University of Leicester, Leicester UK

Daniel P. Kramer, Chadwick D. Barklay,
University of Dayton Research Institute, Dayton, Ohio, US

Jorge García-Cañadas
Universitat Jaume I, Castellón, Spain

Keith Stephenson
European Space Agency, ESTEC, Noordwijk, The Netherlands

Susan White, OSU Reactor Team
Ohio State University, Columbus, Ohio, US

Kevin Simpson, Mark Robbins
European Thermodynamics Ltd., Kibworth, Leicestershire, UK.

Mike Reece, Huanpo Ning, Kan Chen
Queen Mary University of London, London, UK.

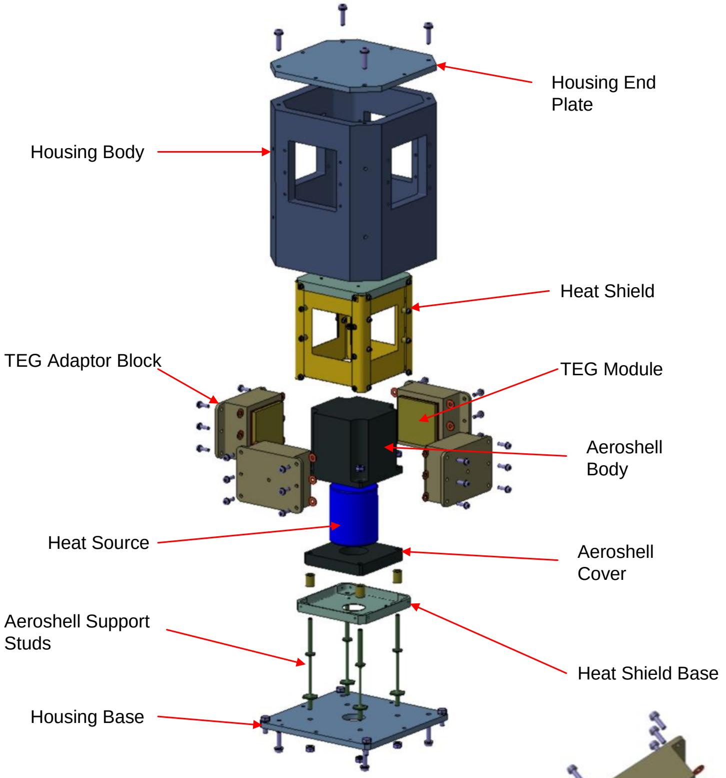
Contents

- European Radioisotope Thermoelectric Generator (RTG) development
  - Update on laboratory ’breadboard’ prototype with upgraded cooling performance.
- Engineering challenges for thermoelectric modules in space RTGs
  - Radiation damage
  - Mechanical properties
- Future work

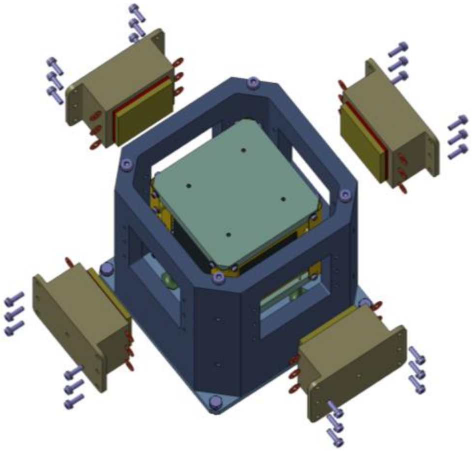
RTG Development in the UK

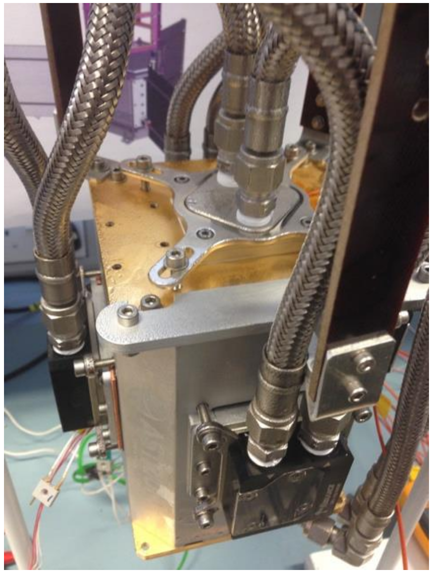
- UoL has led RTG system development in UK under contract to ESA since 2010:
  - PI: Prof. Richard Ambrosi, UoL
- Aim: Develop a first iteration RTG design for Europe optimised for ^{241}Am fuel
- Designed, built and tested a small-scale lab prototype:
  - Target power 5 W_e from 83 W_{th} (electrically heated)
  - Develop a test bed for the integrated system performance of thermoelectric materials & modules
- Produced a 10 W_e refined flight design based on this architecture

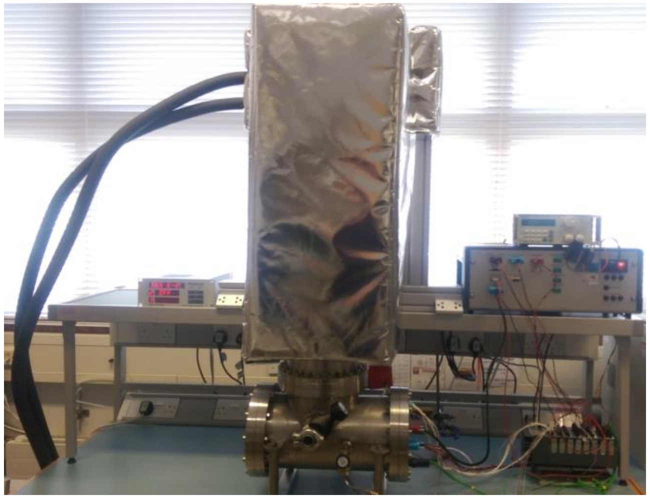
Laboratory RTG System



- 80 W thermal.
- 4.5 W electric.

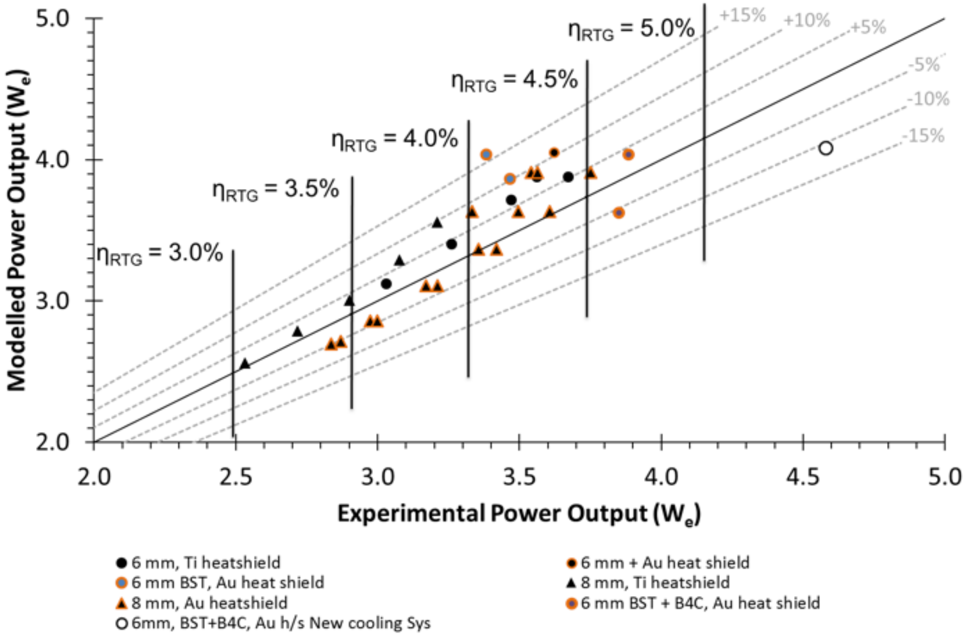


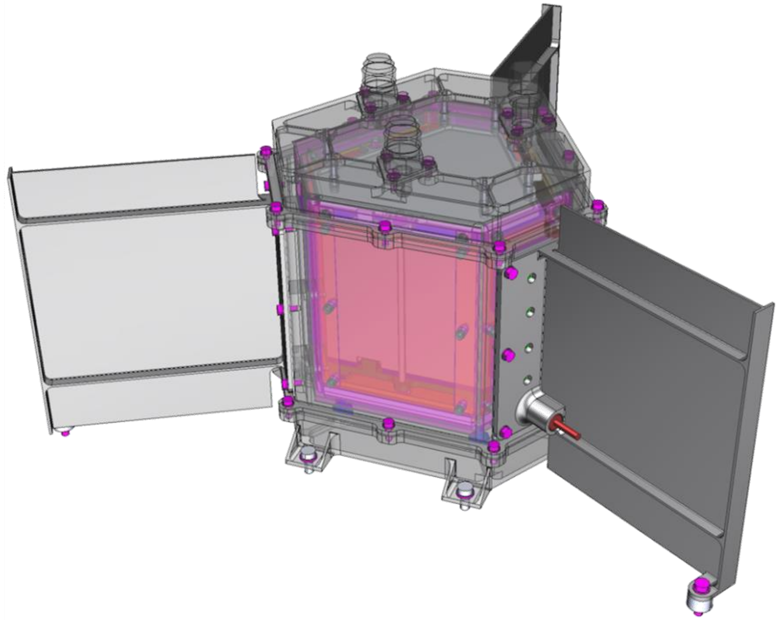




European Design

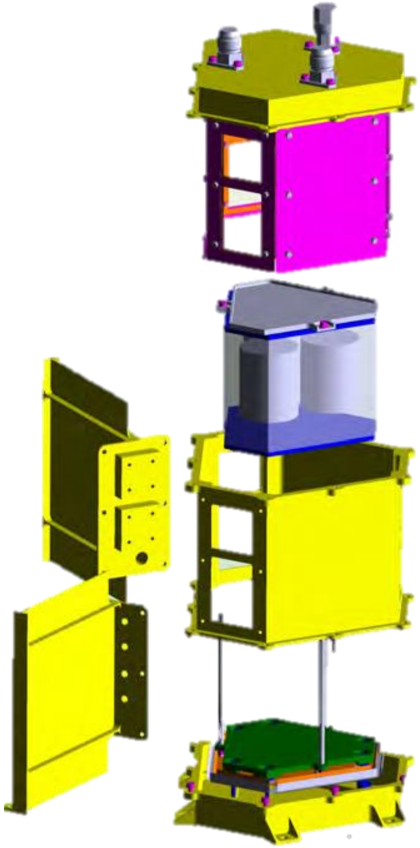
- Lab prototype produced up to ~4.5 W of electrical power, matching predictions and delivering an efficiency ~5.5%.

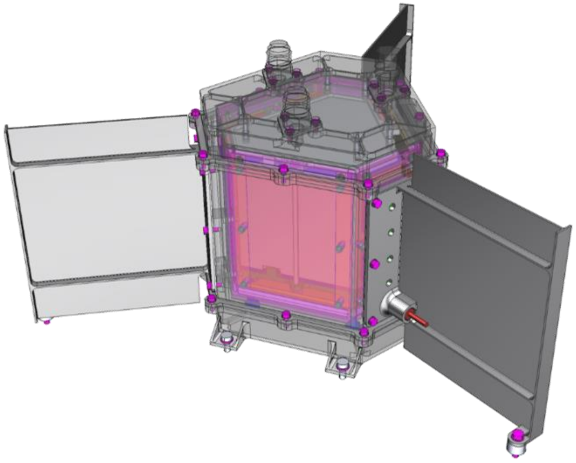




- Flight design would produce 10 W of electrical power.
- Flight designs would be scalable to 50 W.
- Flexibility to tailor to mission requirements.

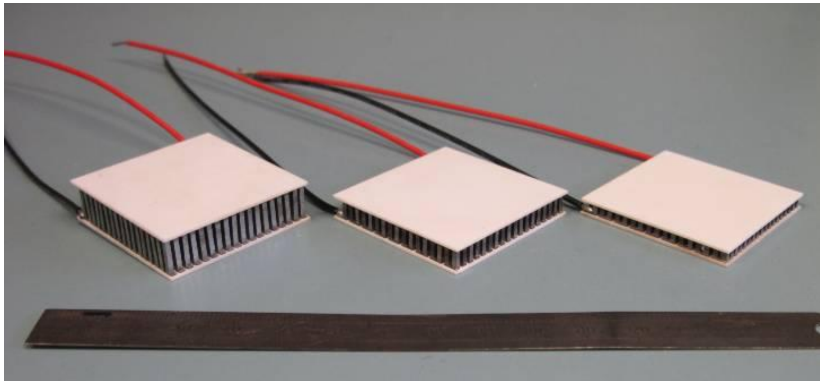
RTG Architecture & implications





For the thermoelectrics:

- Bi_2Te_3 based materials
- Compression & shear loading
- Modules with high aspect ratio legs



RTG Neutron Emission

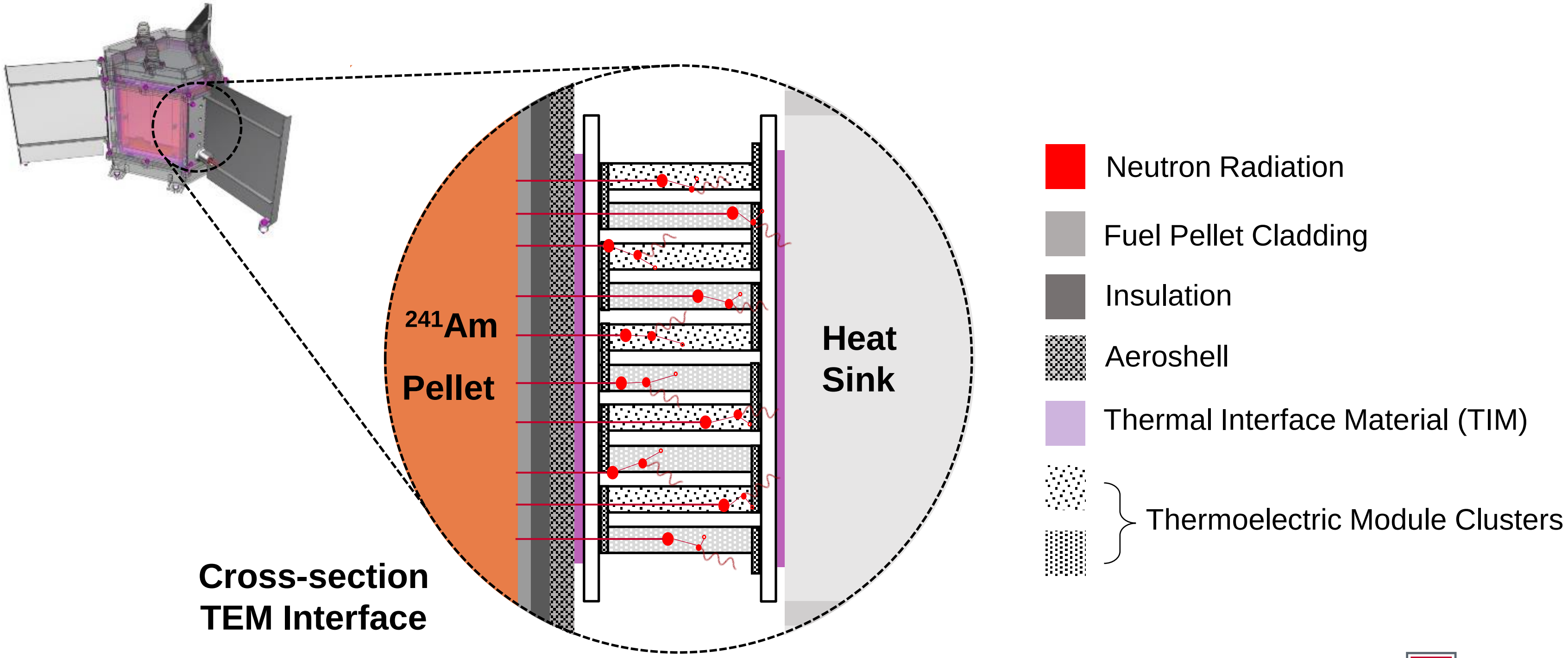
Assuming a 10 year life span

5 years of initial exposure

System assembly and integration, storage, transfer to launch site and then integration on spacecraft and finally launch.

5 year nominal mission exposure

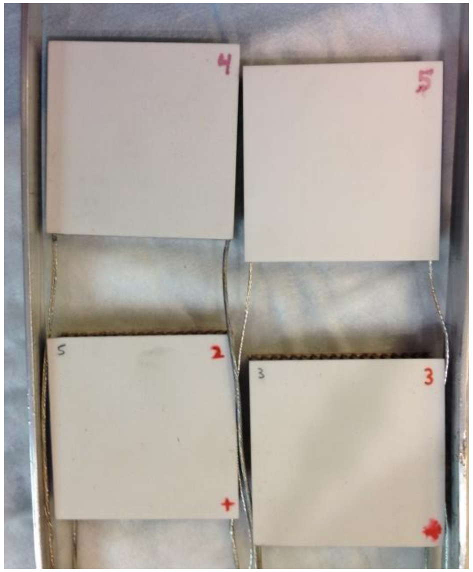
~ 5×10^{13} n/cm^2 **(>1MeV)**

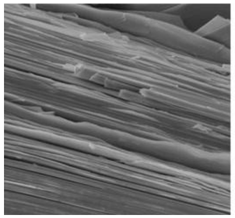


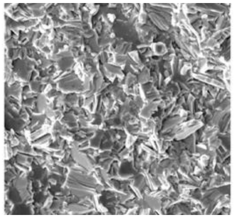
Literature Review

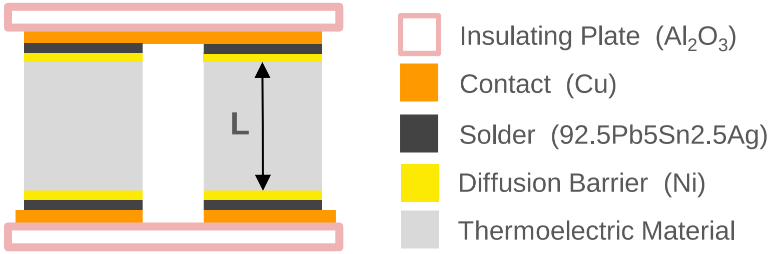
			Total Integrated Flux					
Research group	Year	Specimen	Thermal	>1Mev	$\frac{S_1{}^{1}}{S_2{}^{0}}$	$\frac{\rho_1{}^{1}}{\rho_2{}^{0}}$	$\frac{\lambda_1{}^{1}}{\lambda_2{}^{0}}$	Annealing Temp (˚C)
Danko et al. [1]	1962	$Bi_{0.05}Ge_{0.95}Te$	9.4×10^{18}		1.15	1.10	~	300
Danko et al. [1]	1962	$Bi_{0.05}Ge_{0.95}Te$	2.7×10^{19}	1.5×10^{20}	2.40	2.00	~	300
Corelli et al. [2]	1960	Bi_2Te_3 -n type	1.5×10^{20}	1.6×10^{19}	1.16	5.00	0.88	200
Corelli et al. [2]	1960	Bi_2Te_3 -n type	~	1.6×10^{19}	1.04	2.60	~	200
Idnurm et al. [3]	1967	Bi_2Te_3 -n type	2.0×10^{18}	~	1.03	1.13	0.96	~
Corelli et al. [2]	1960	Bi_2Te_3 -p type	1.5×10^{20}	1.6×10^{19}	-1.05	2.00	~	200
Corelli et al. [2]	1960	Bi_2Te_3 -p type	~	1.6×10^{19}	-0.82	1.2	~	200
Idnurm et al. [3]	1967	Bi_2Te_3 -p type	2.0×10^{18}	~	1.00	1.13	0.98	~
Idnurm et al. [3]	1967	Bi_2Te_3 - Sb_2Te_3 -n type	2.0×10^{18}	~	0.95	1.18	0.97	~
Idnurm et al. [3]	1967	Bi_2Te_3 - Sb_2Te_3 -p type	2.0×10^{18}	~	0.99	0.93	1.02	~

Pre-irradiation Characterisation




Directional

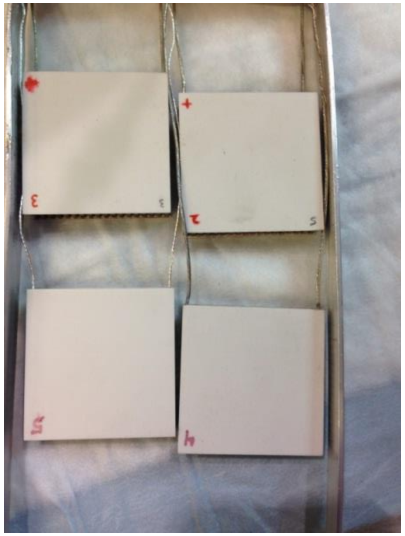

Polycrystalline



☐ Insulating Plate (Al_2O_3)
🟧 Contact (Cu)
■ Solder (92.5Pb5Sn2.5Ag)
🟨 Diffusion Barrier (Ni)
▨ Thermoelectric Material

Module No.	P-type	N-type	Crystallographic Structure	L (mm)	No. of Couples
2	Bi_2Te_3	Bi_2Te_3	Directional Solidification	8	161
3	Bi_2Te_3	Bi_2Te_3	Directional Solidification	8	161
4	Bi_2Te_3	Bi_2Te_3	Directional Solidification	6	161
5	$Bi_{0.5}Sb_{1.5}Te_3$	Bi_2Te_3	p - Polycrystalline n - Directional Solidification	6	161

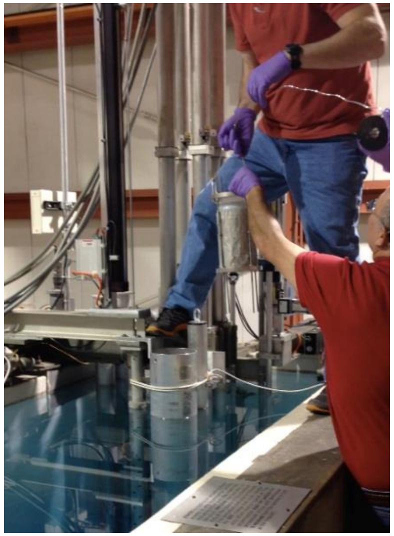
TEG Irradiation Procedure



TEG hanger assembly

Cadmium shielded enclosure

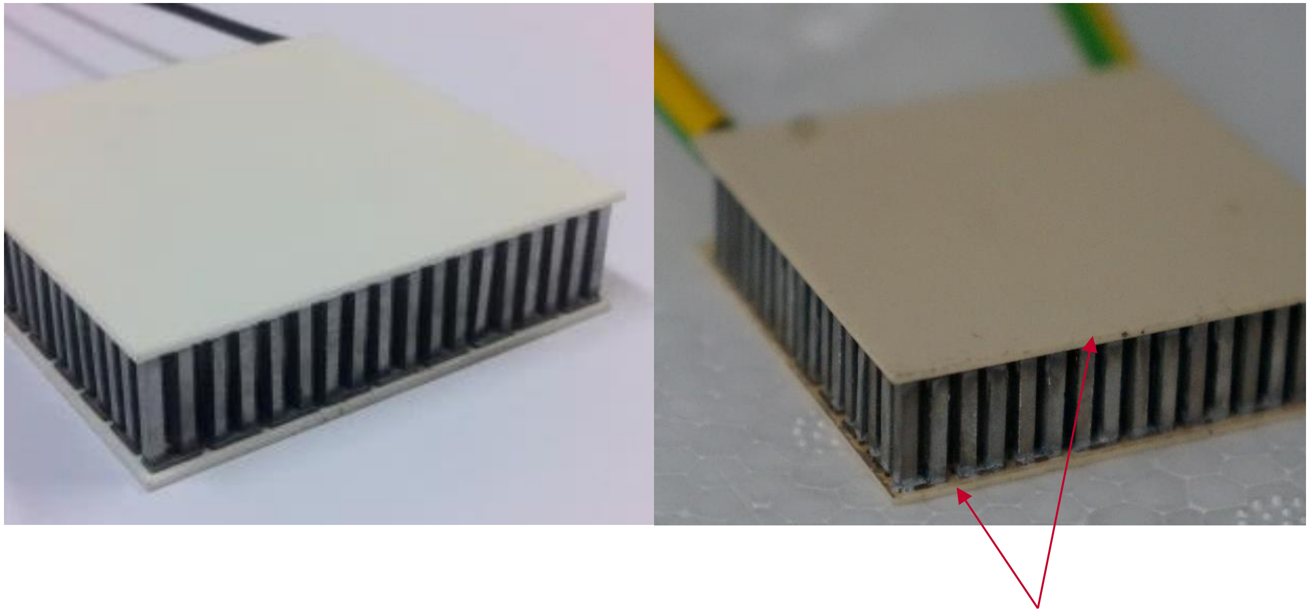
Placing into dry tube



Acute 2hr exposure

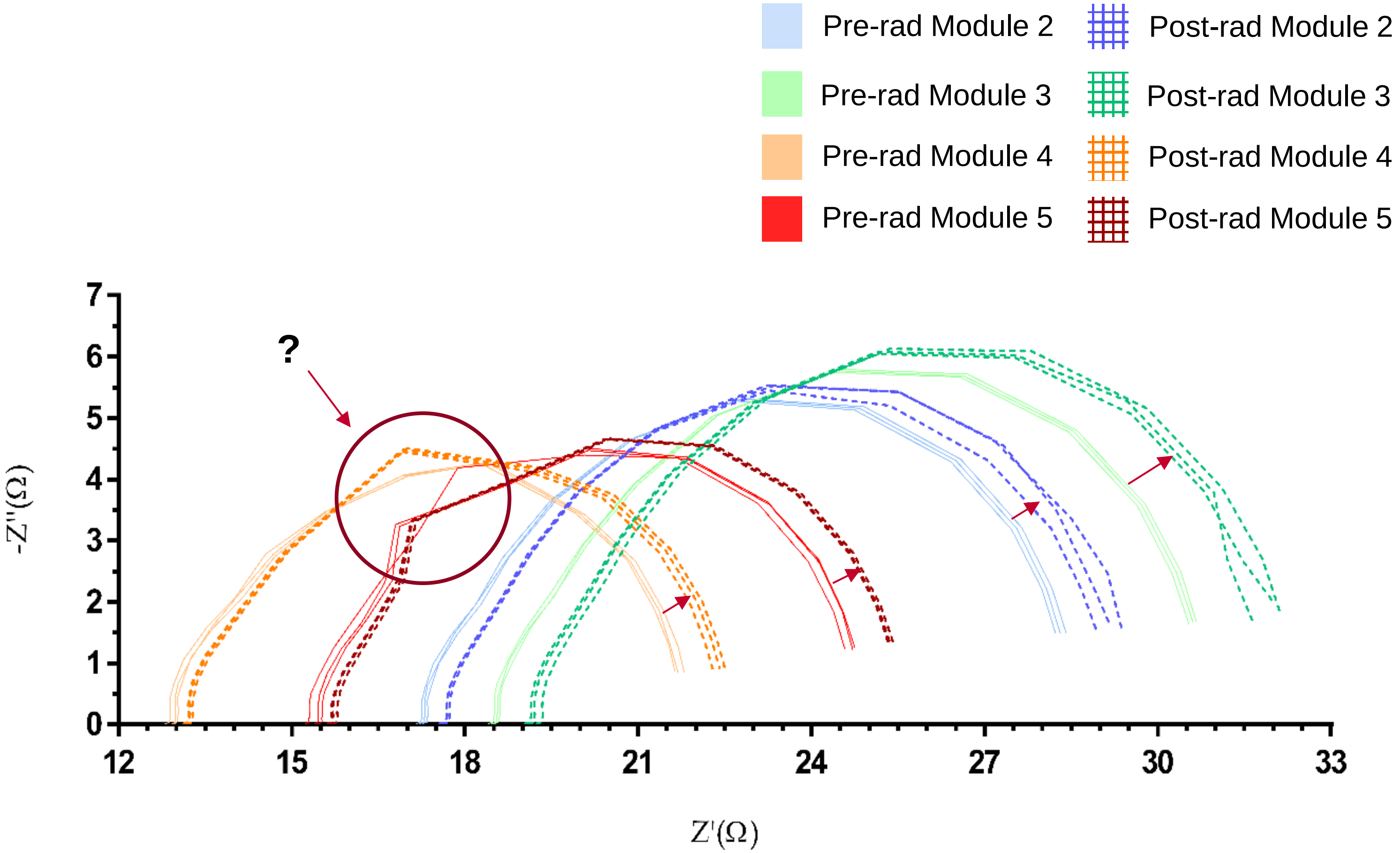
Post-irradiation Observations

Pre **Post**

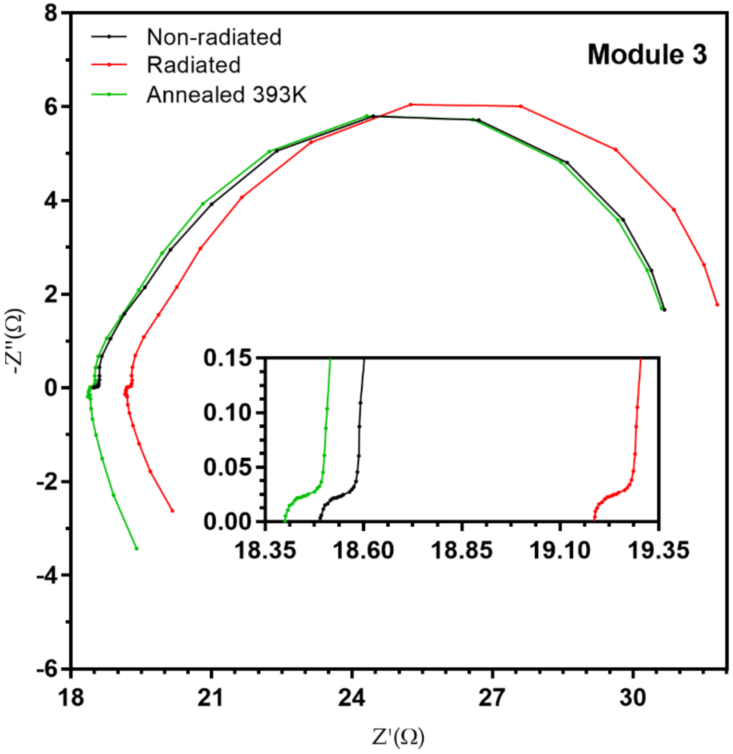


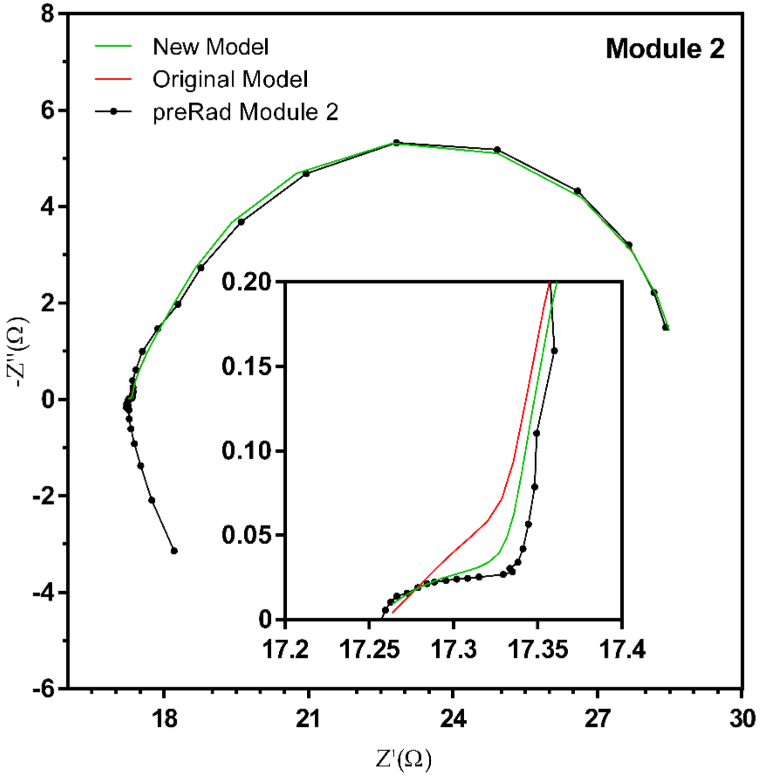
Discolouration

Impedance Spectroscopy



Impedance Spectroscopy

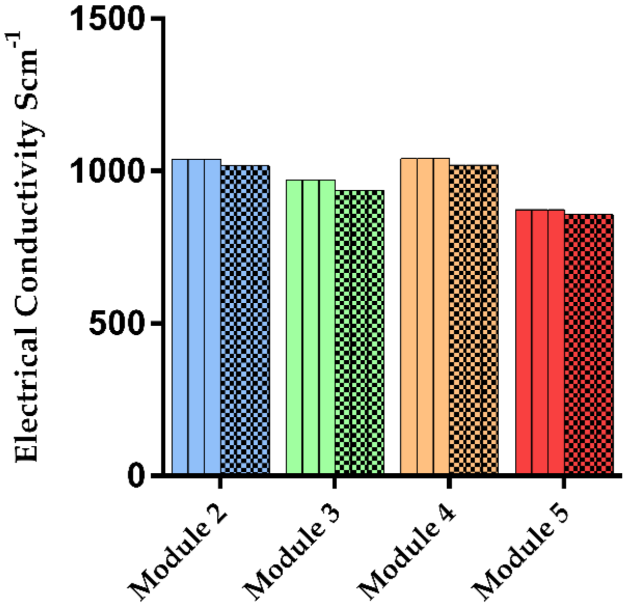


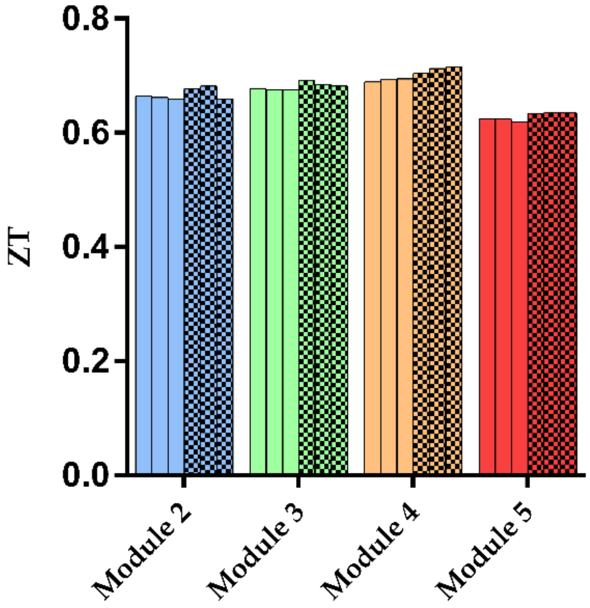


Thermoelectric Properties

~2% increase in Resistivity

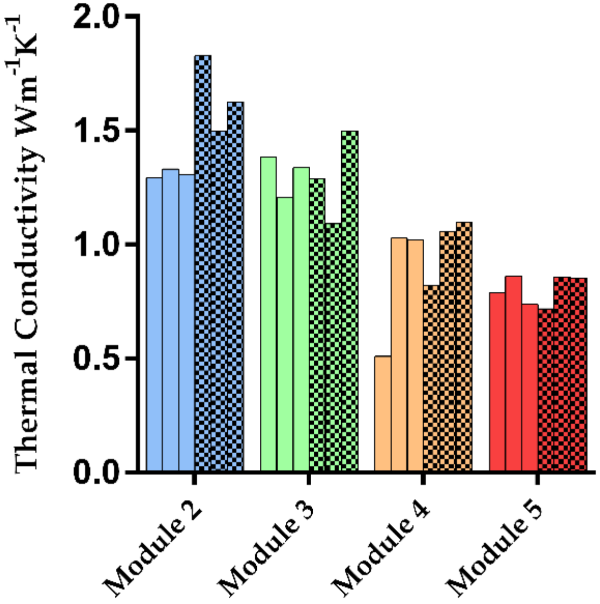
~2% increase in ZT

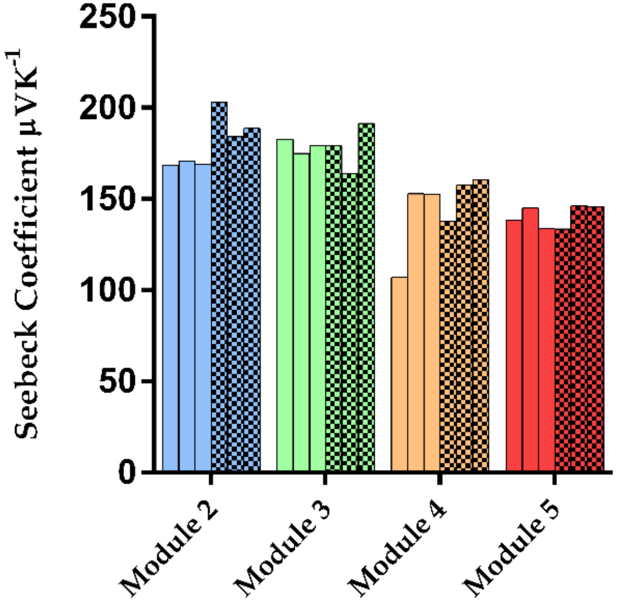




Thermoelectric Properties

Peak increases observed however results suffer greater variation

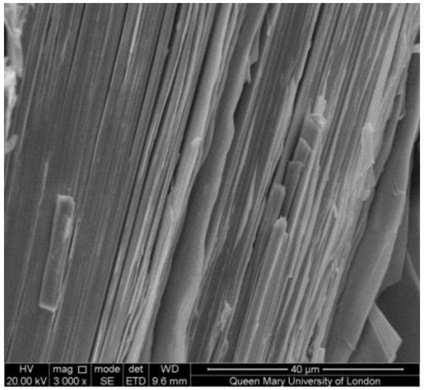




Enhanced Bi_2Te_3 thermoelectrics

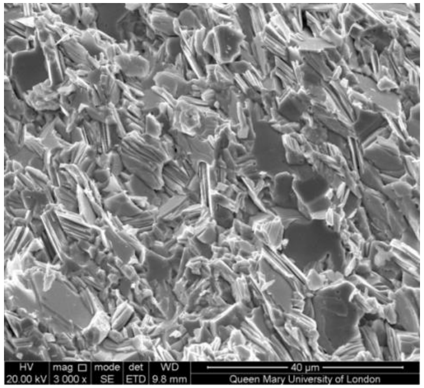
- Most active research on thermoelectric materials focuses on zT
- Mechanical properties and behaviour of materials and modules is under-represented in the literature.

Conventional material production is by directional solidification



← Very poor strength and/or toughness due to cleavage along the basal crystallographic plane || to growth

Polycrystalline, fine grained materials: better mechanical properties



Williams HR et al. 2015. Spark Plasma Sintered bismuth telluride-based thermoelectric materials incorporating dispersed boron carbide. *Journal of Alloys and Compounds.* **626**. 368-374.

Queen Mary University of London

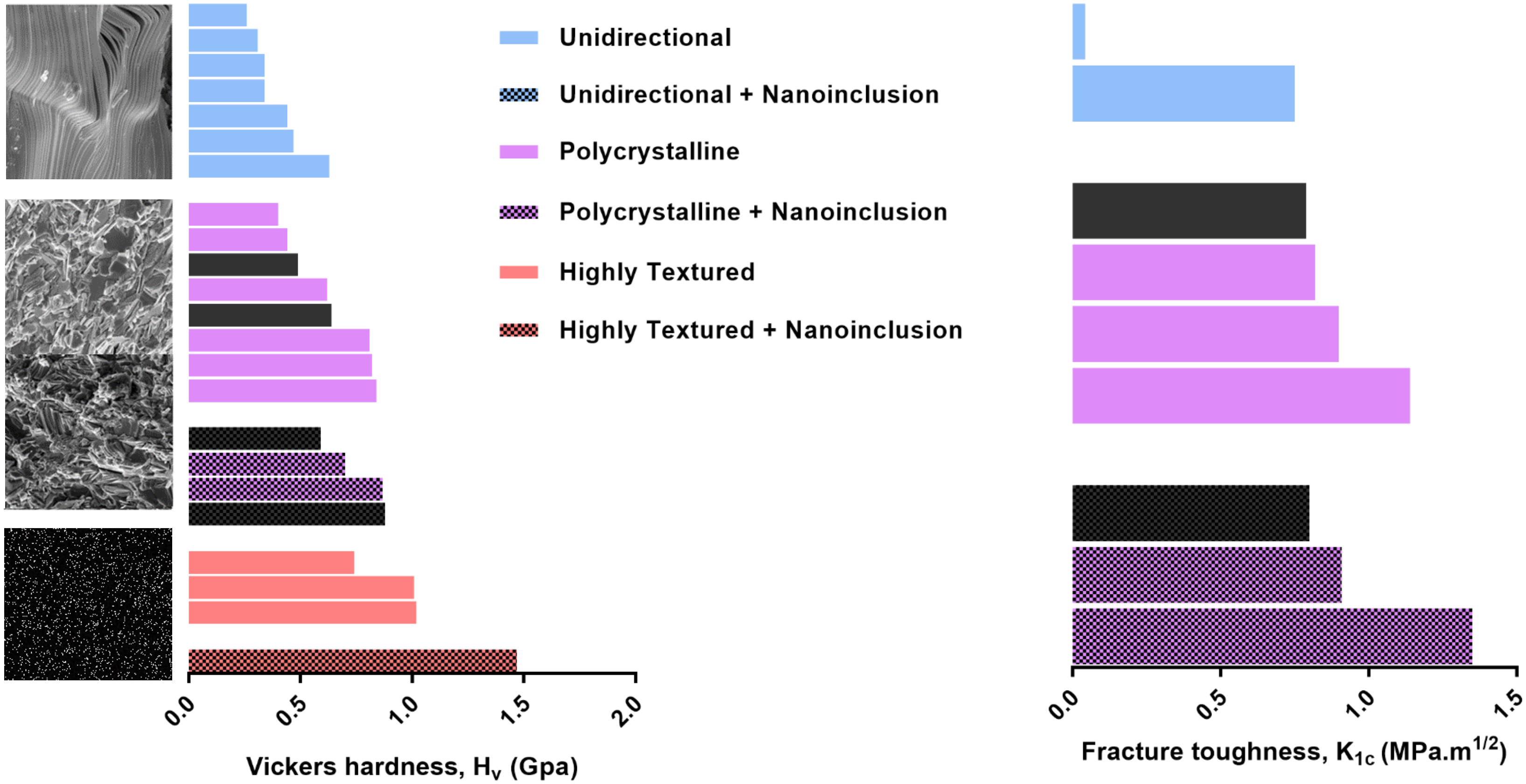
European Thermodynamics Limited
Intelligent Thermal Management

UNIVERSITY OF LEICESTER

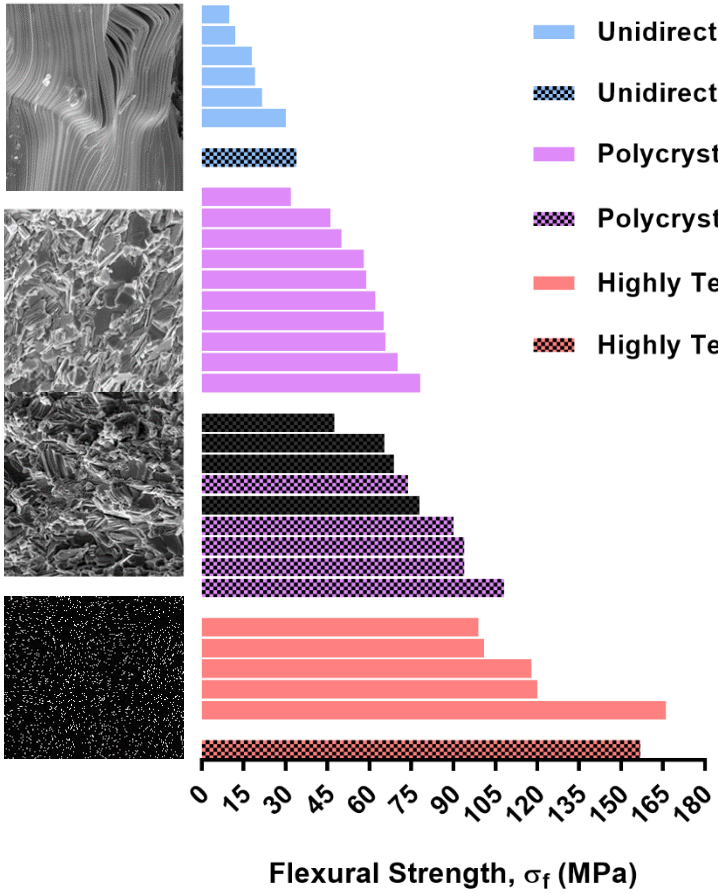
Room Temperature Characterisation

Property		Procedure	Coupon Size	Sample Size	Statistical Analysis
σ_f	Flexural Strength	ASTM C1161 (4pt-Bending)	1.5 x 2.0 x 25 mm^3	30	Weibull
K_{Ic}	Facture Toughness	ISO 23146 (SEVNB)	3.0 x 4.0 x 25 mm^3	30	N/S
E	Elastic Modulus	ISO 14577 (Nanoindentation)	N/S	30	N/S
H	Hardness	ASTM C1327 (Vickers Indentation)	N/S	30	N/S

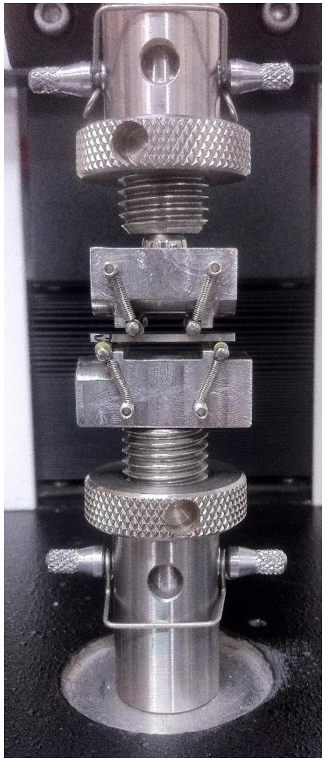
Hardness & Fracture Toughness



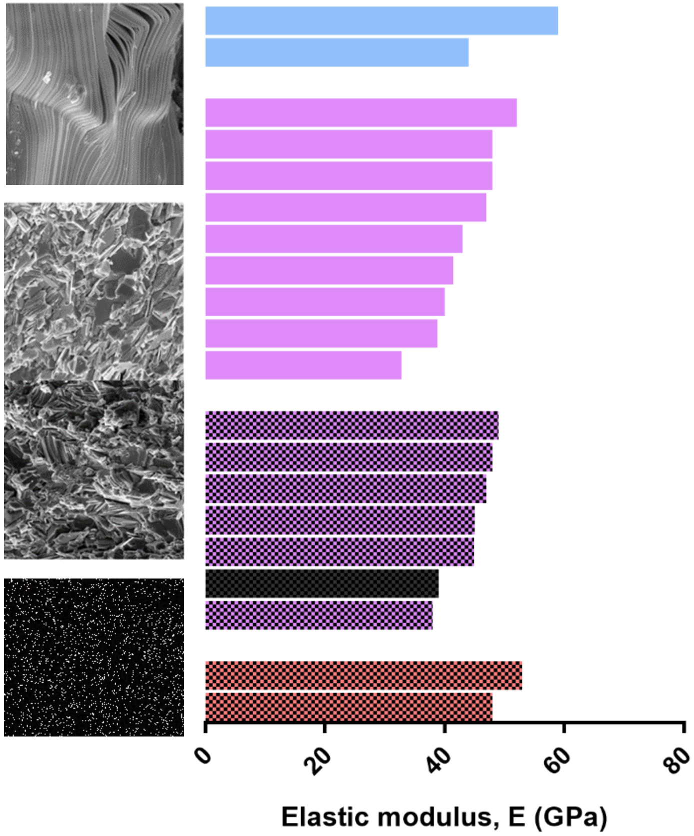
Flexural Strength Testing

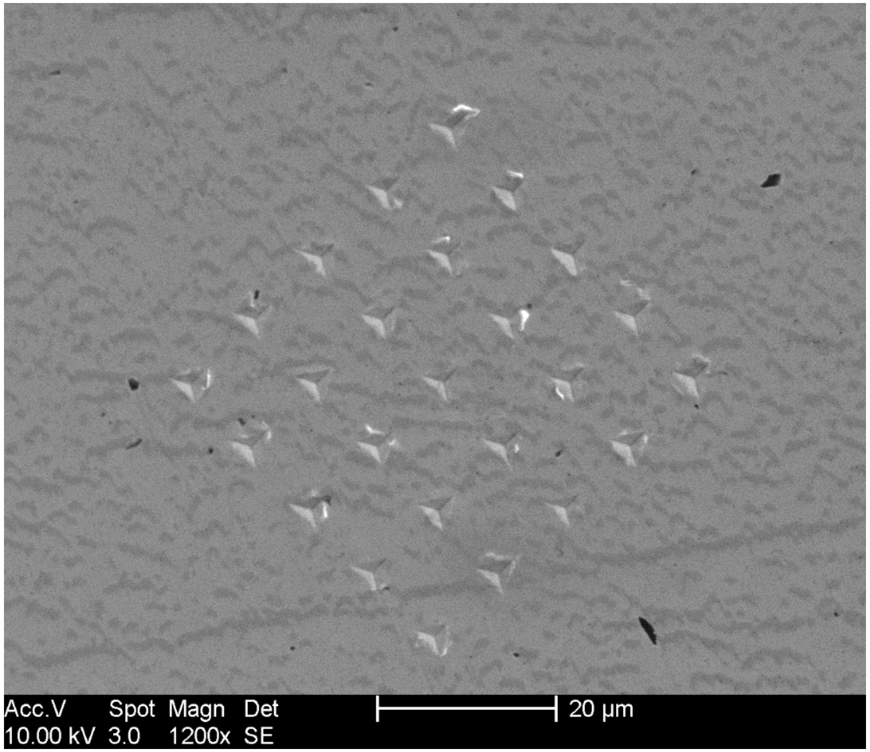


500N Instron



Elastic Modulus





- 🟦 **Unidirectional**
- ▩ **Unidirectional + Nanoinclusion**
- 🟪 **Polycrystalline**
- ▩ **Polycrystalline + Nanoinclusion**
- 🟥 **Highly Textured**
- ▩ **Highly Textured + Nanoinclusion**

Future Work

- Flight-like RTG lab prototype under development.
- Radioisotope Heater Unit Porotype also under development for ESA.
- Impedance spectroscopy shows promise for module level characterisation even if just on a comparative level.
- Devise a more robust and repeatable Impedance spectroscopy characterisation experimental setup.
- Further improve Impedance spectroscopy fitting.
- Investigate mechanical properties changes due to texturing on n-type bismuth telluride using a hot forging process combined with SPS