Office Of Nuclear Energy Sensors and Instrumentation Annual Review Meeting

Nanostructured Bulk Thermoelectric Generator for Efficient Power Harvesting for Self-powered Sensor Networks

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NEET2

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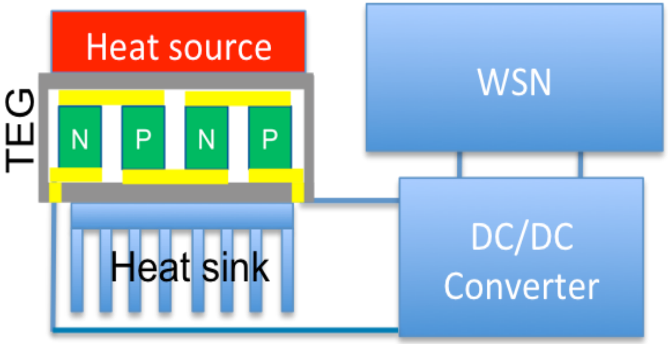
Project Overview

Goal, and Objectives

- Develop high-efficiency and reliable thermoelectric generators (**TEG**s)
- Demonstrate self-powered wireless sensor nodes (**WSN**s)

Participants

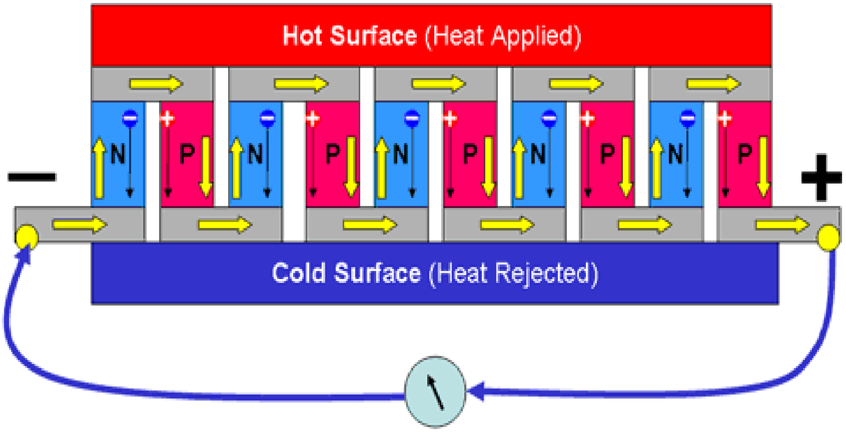
- Yanliang Zhang, Boise State University;
- Brian Jaques, Boise State University;
- Vivek Agarwal, Idaho National Laboratory;
- Zhifeng Ren, University of Houston.



Schedule 01/2015 - 12/2017

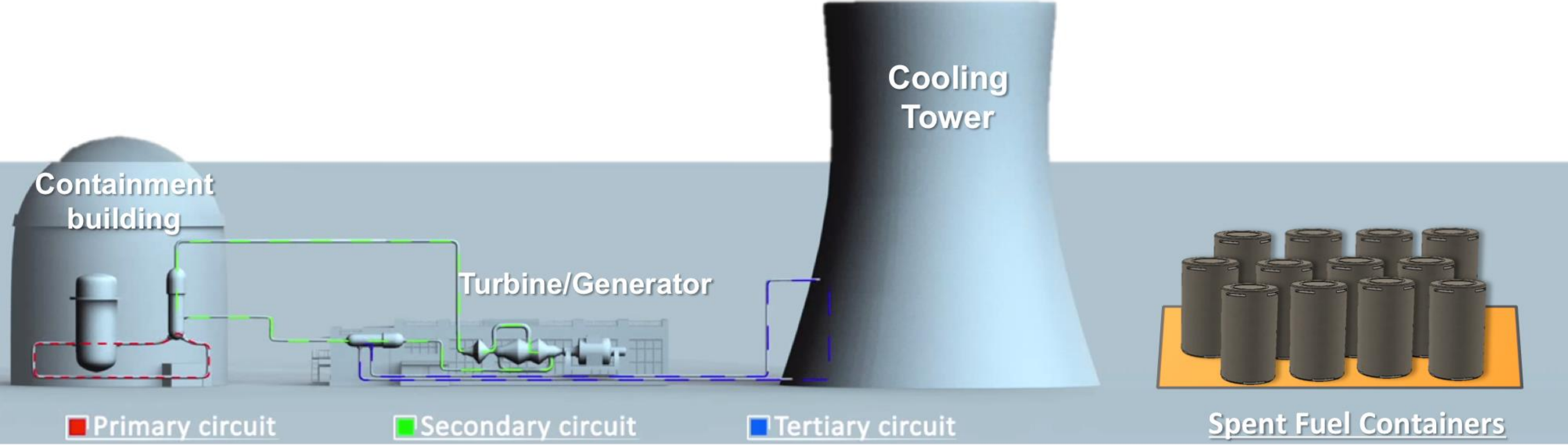
Year 1	• Determine and profile WSN power consumption • Select thermoelectric materials with optimal performance • Study irradiation effect on thermoelectric materials
Year 2	• Develop a TEG and WSN simulator • Design TEG of sufficient power output • Complete analysis of irradiation effect
Year 3	• Fabricate the TEG and test the TEG under irradiation effect • Demonstrate the TEG-powered WSN prototype

Background and motivation



Thermoelectric Generator (TEG)

- TEG is very compact and reliable
- Heat sources are very abundant in nuclear power plant and fuel cycles
- The nanostructured bulk thermoelectric materials have significantly higher efficiency and potentially improved radiation resistances over commercial bulk materials.



Accomplishments

- **The team achieved the following milestones for FY16**

- Fabricated high-temperature and high-power-density thermoelectric generators (TEGs)

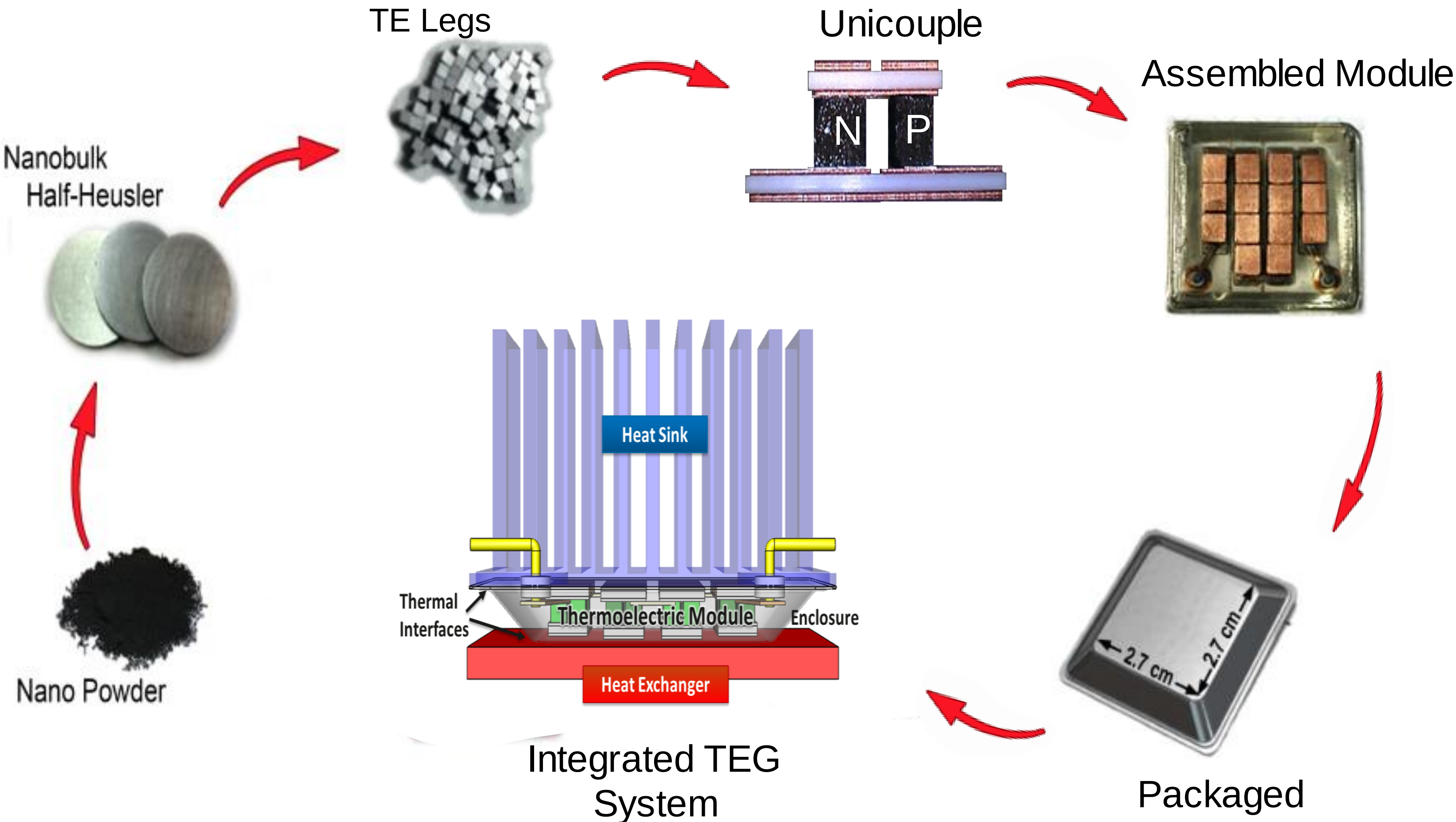
- Developed flexible TEGs by screen printing

- Performed comprehensive study of irradiation effect on thermoelectric materials

- Established wireless sensor node power requirements

- Built initial self-powered wireless sensor node prototype

TEG Fabrication Process Flow



Nano Powder

Nanobulk Half-Heusler

TE Legs

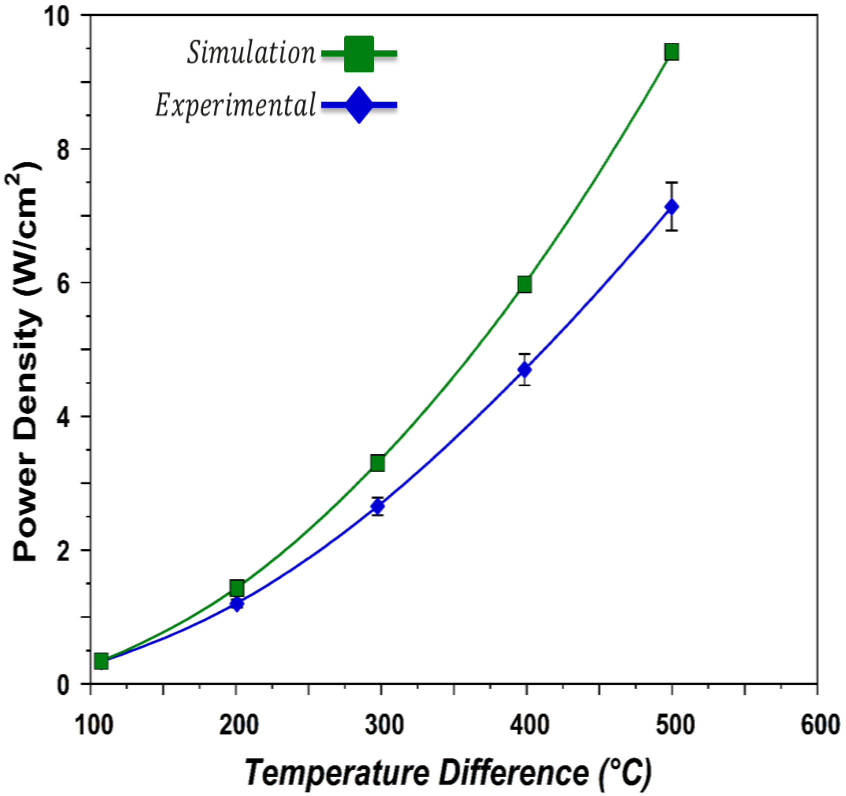
Unicouple

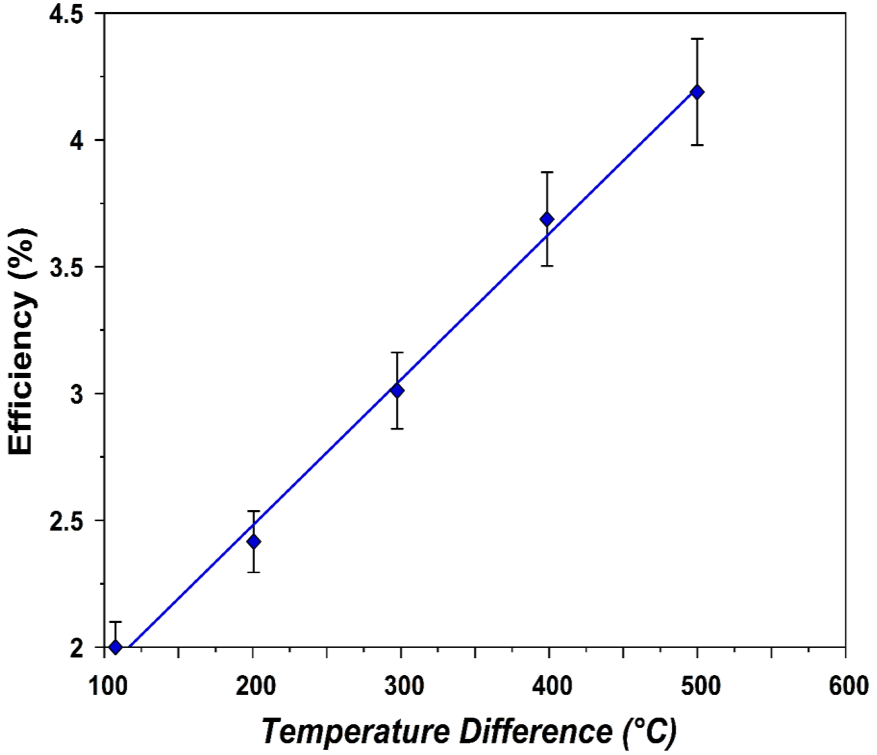
Assembled Module

Packaged Device

Integrated TEG System

TEG Device Testing Results

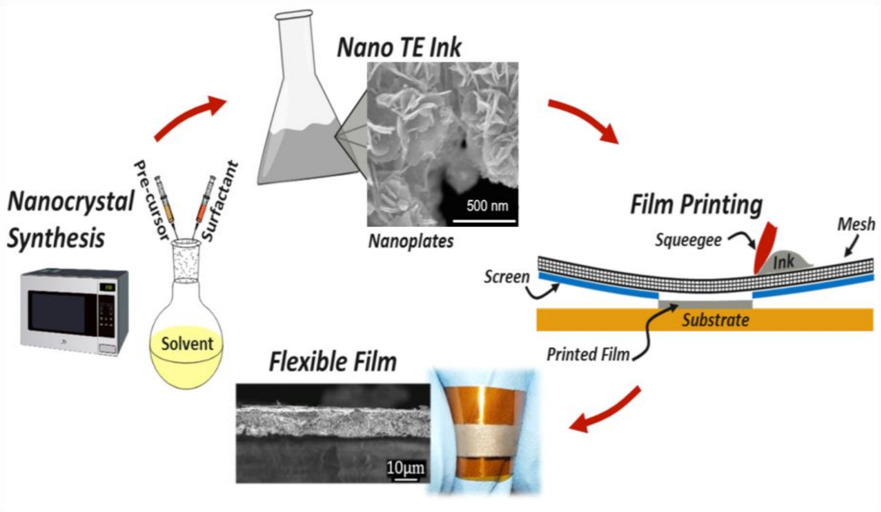


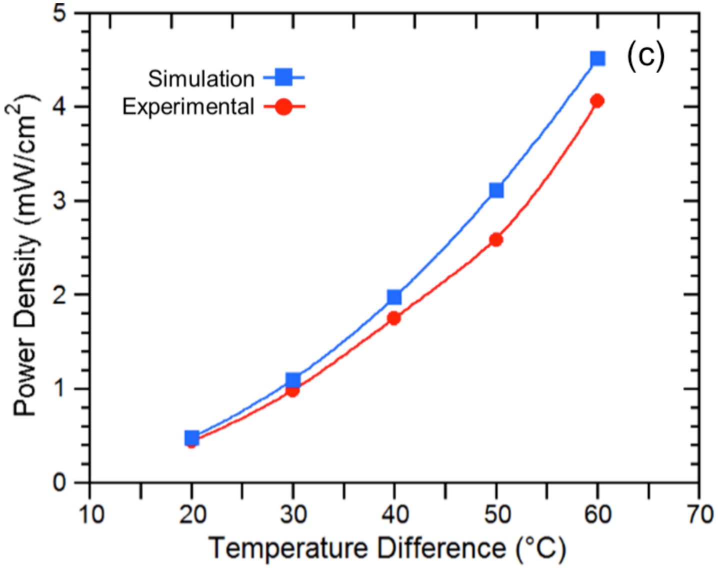


- Simulation is done with ideal electrical and thermal contacts
- Actual device power density lower than simulation due to parasitic losses

Flexible thermoelectric generator fabricated by screen printing

- BSU developed a novel additive printing process to fabricate flexible TE materials and devices
- The printed flexible film showed very high ZT of 0.43, among highest in printed materials
- A flexible thermoelectric device produces a high power density of 4.1 mW/cm^2 with only 60 ºC ΔT

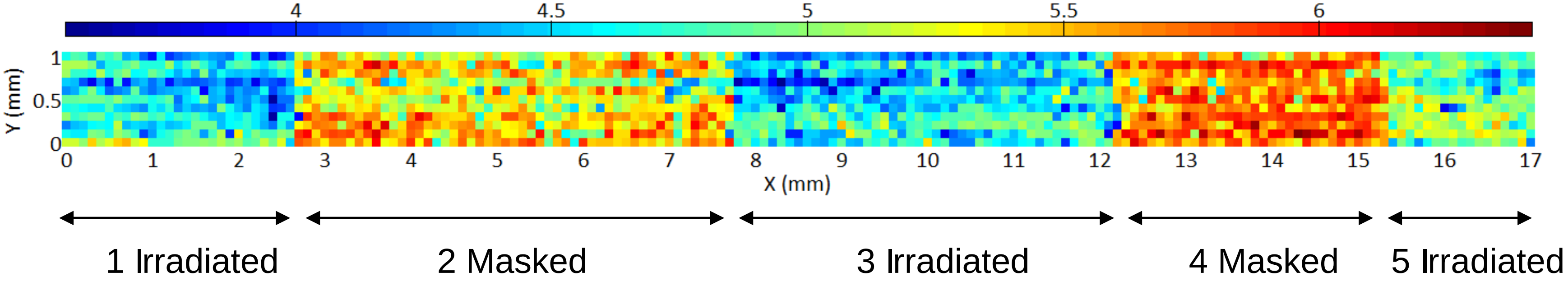




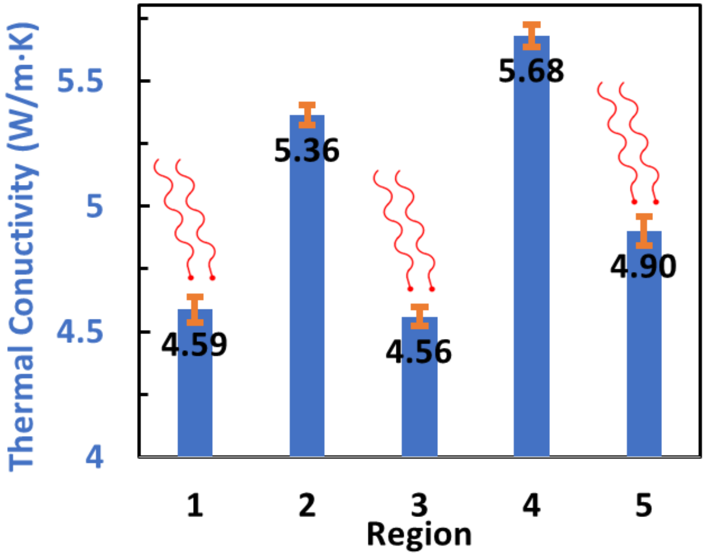
T. Varghese, C. Hollar, N. Kempf, C. Han, D. Estrada, R. J. Mehta, **Y. Zhang**, High-performance and flexible thermoelectric films by screen printing solution-processed nanoplate crystals, ***Scientific Reports***, 6, 33135, 2016.

Proton irradiation effect on nanostructured thermoelectric materials

2D Property Map: Thermal Conductivity (W/m·K)



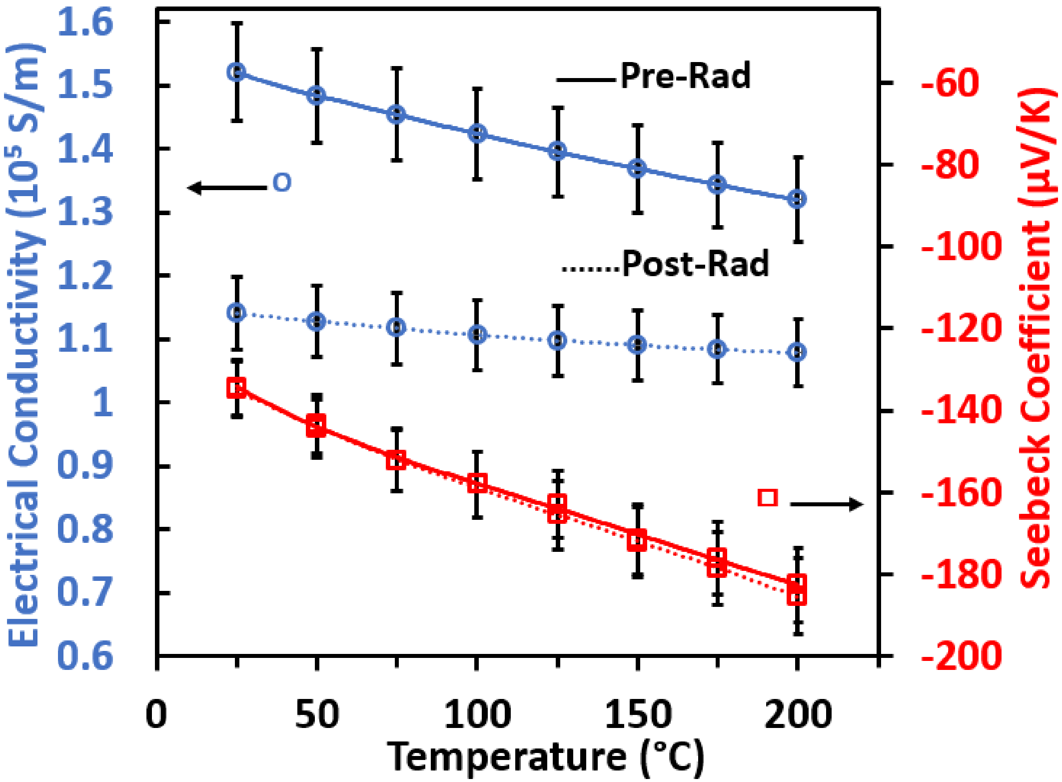
- **Material studied: N-Type half-Heusler $Hf_{0.25}Zr_{0.75}NiSn_{0.99}Sb_{0.01}$**
- **Irradiation conditions: 2.5 MeV protons at 100 nA and $2\cdot10^{16}$ ions/cm^{2}**



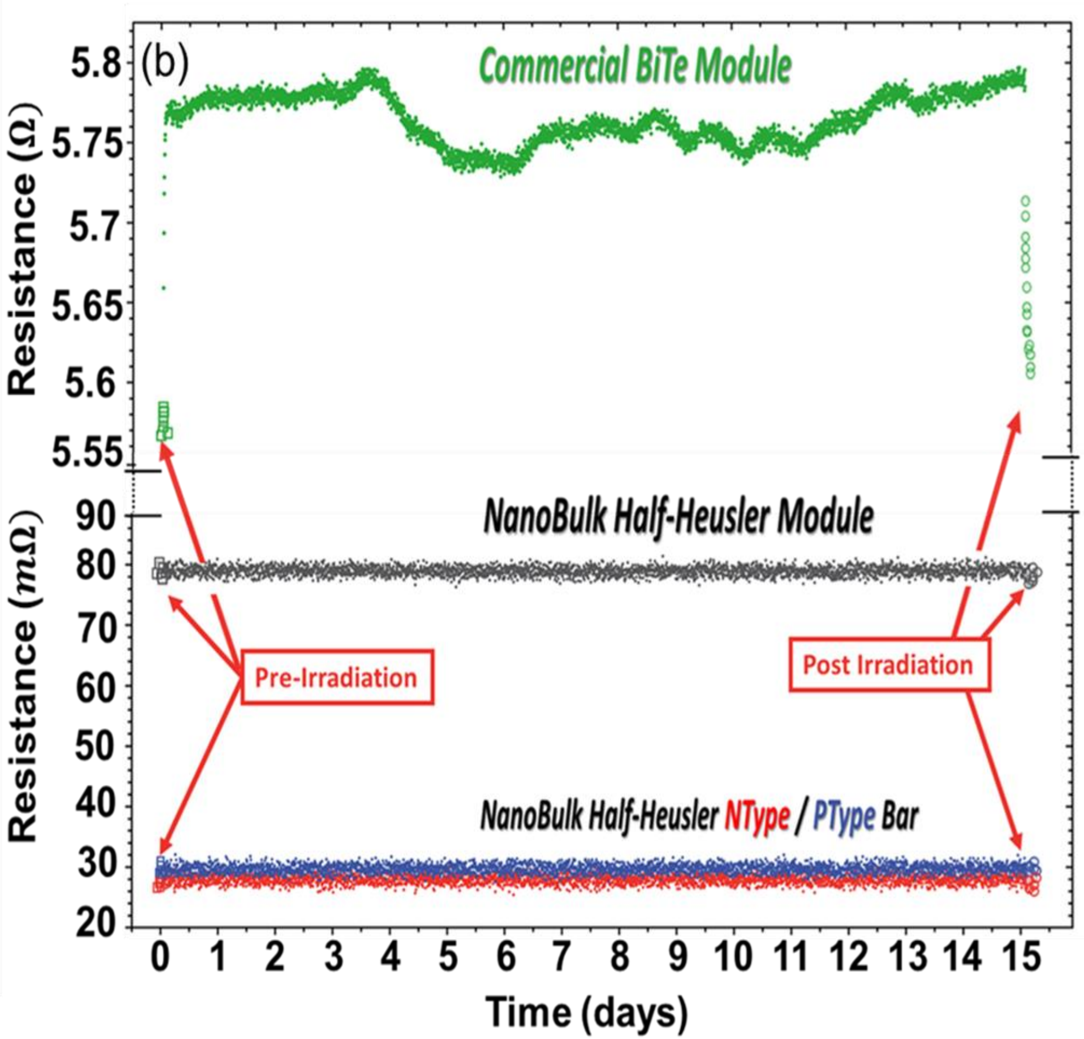
- 16% thermal conductivity reduction due to proton irradiation

Proton irradiation effect on nanostructured thermoelectric materials

- A 35 µm thick film was also measured before and after irradiation
- 25% reduction in electrical conductivity at room temperature, 18% reduction at 200° C
- No change in Seebeck coefficient
- Overall 10% reduction in thermoelectric figure of merit ZT



Gamma irradiation: in-situ resistance testing

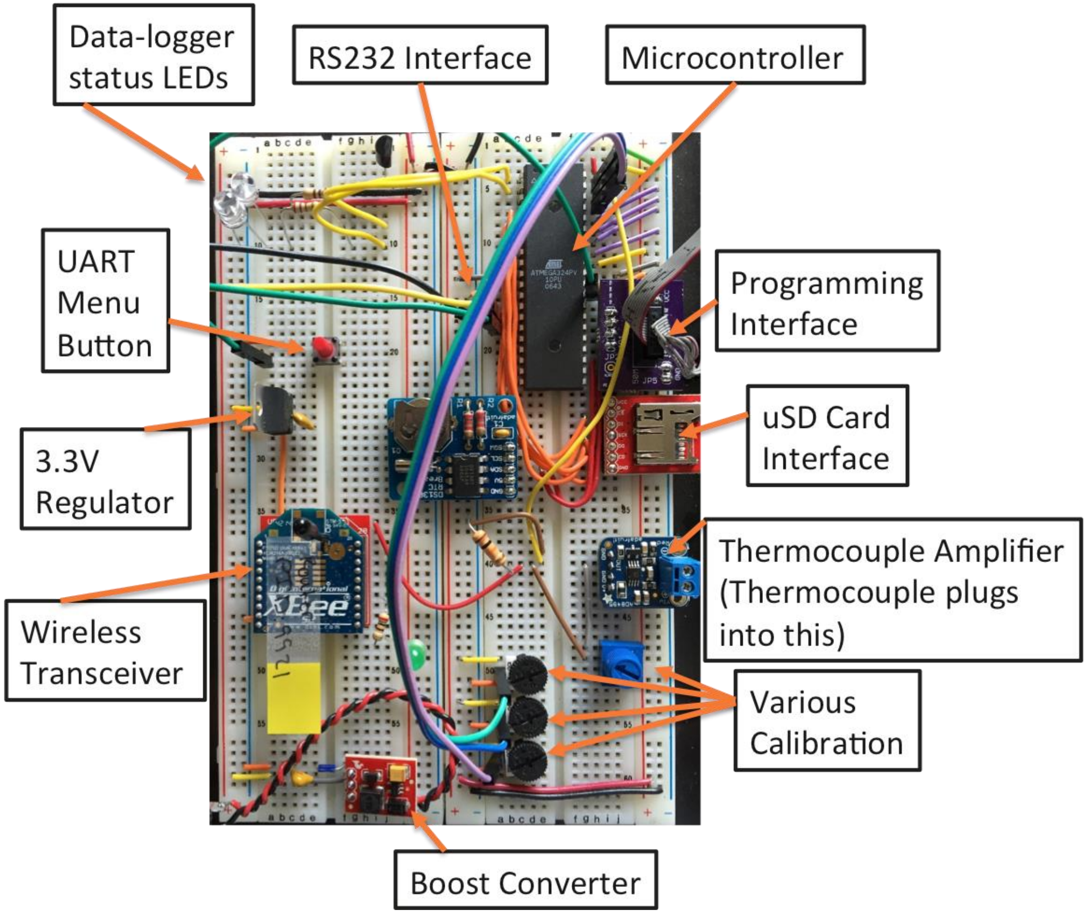


- Average dose rate: 6.14 kGy/hour
- Total received dose: 2360 kGy

- ~3.5% increase in resistivity of commercial BiTe module
- No measureable change in any nanostructured bulk half-Heusler device

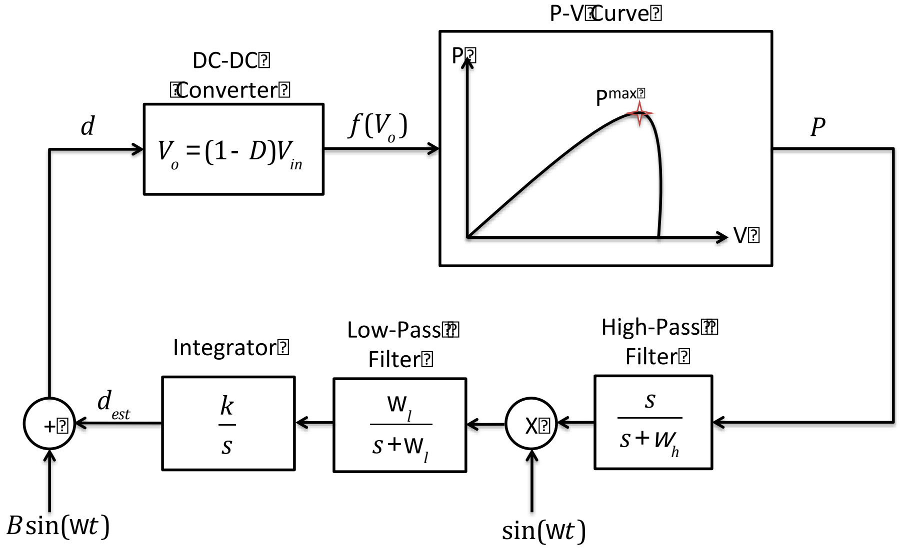
Integration of TEG and WSN to demonstrate self-powered WSN

- Built and tested a self-powered wireless sensor node powered by TEG
- The WSN is based on Zigbee communication
- Low power consumption of < 0.4 Watts while running
- Remote capability to view and log current data through a secure Zigbee connection
- Transmission distance of up to 120 meters
- No interference with existing wireless networks



Design maximum power point tracking algorithm

- Implemented extremum seeking control (ESC) algorithm for Maximum Power Point Tracking (MPPT) in MATLAB®.
- Compared the result with Perturb and Observe (P&O) algorithm and with fixed duty-cycle operation



Block diagram of ESC Algorithm implemented in MATALB

Temperature (C)	Theoretical P(W)	P&O P(W)	ESC P(W)	Fixed duty cycle P(W)
450	0.04299	0.04221	0.04280	0.03680
400	0.02952	0.02876	0.02906	0.02704
350	0.01869	0.01814	0.01834	0.01576

Comparison of estimated MPP using P&O and ESC algorithms.

Technology Impact

Impact on overall NE mission and the nuclear industry

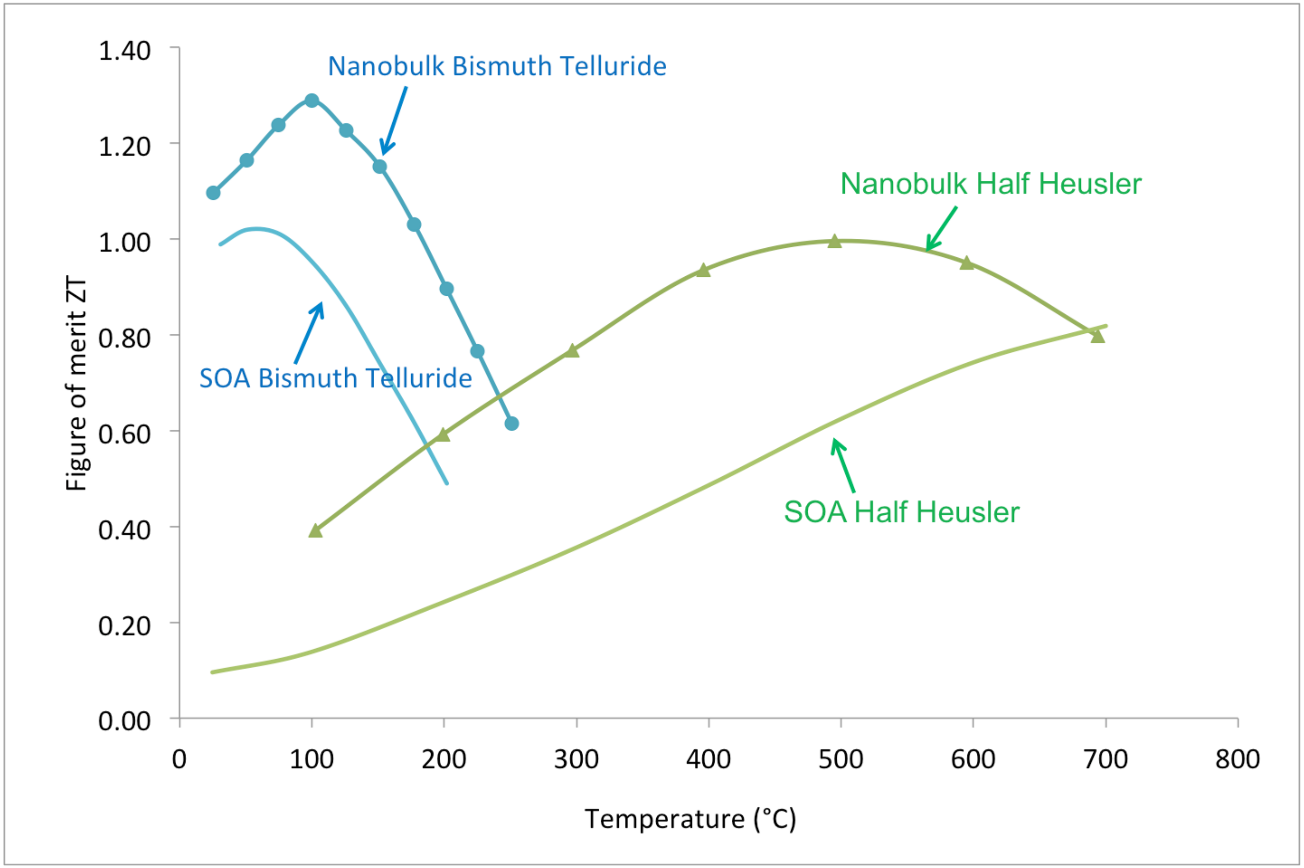
- Address critical technology gaps in monitoring nuclear reactors and fuel cycle.
- Enable self-powered WSNs in multiple nuclear reactor designs as well as spent fuel storage facilities.
- Cost savings by eliminating cable installation and maintenance.
- Significant expansion in remote monitoring of nuclear facilities.
- Significantly improve sensor power reliability and thus safety in nuclear power plants and spent fuel storage facilities.

Conclusions

- Developed high-temperature and high-power density TEGs
- Developed flexible TEGs for power harvesting near ambient temperature
- Performed comprehensive study on irradiation effect on thermoelectric materials. The nanostructured TE materials showed robust performances under proton and gamma irradiation
- Built a WSN and tested the power consumption based on Zigbee protocol, and demonstrated an initial self-powered WSN prototype using a compact TE generator
- The TEGs we developed showed promises to be used for power harvesting in wide range of nuclear power plant facilities.

Addition information

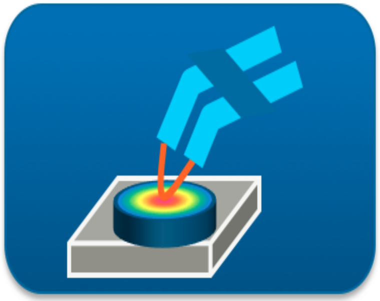
Enhanced thermoelectric efficiency in nanostructured materials

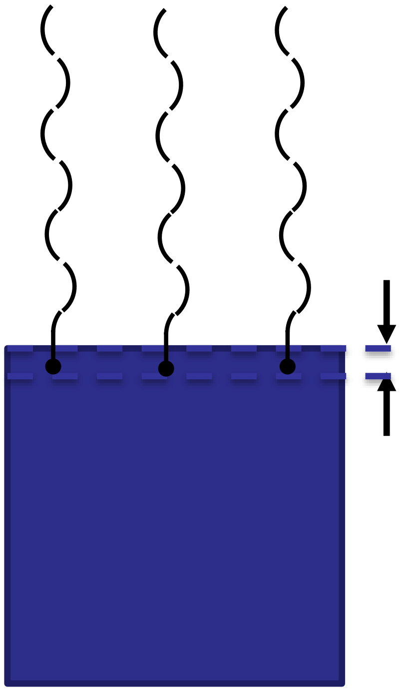


- Our nanostructured thermoelectric materials have shown 30-50% ZT increases

Measuring thermoelectric property changes before and after radiation

Approach 1: Scanning Thermal Probe Microscopy (SThM)

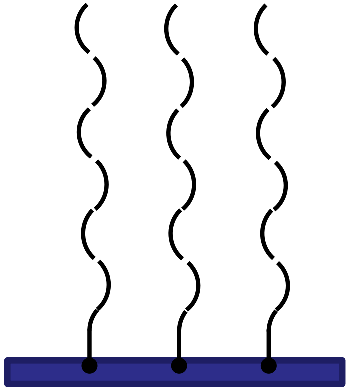




Damaged Region

Simultaneously measure thermal conductivity and Seebeck coefficient

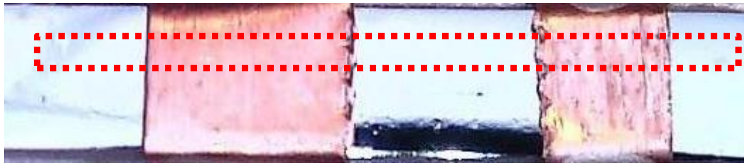
Approach 2: Nanostructured Thin Films



Entire depth is irradiated

Irradiation effect on nanostructured thermoelectric materials

- **Material studied: N-Type half-Heusler $Hf_{0.25}Zr_{0.75}NiSn_{0.99}Sb_{0.01}$**
- **Irradiation conditions: 2.5 MeV protons at 100 nA and $2 \cdot 10^{16}$ ions/cm²**
- **A bulk bar with selected regions masked by copper bridges was irradiated**
- **Using SThM, we compare thermal conductivity and Seebeck coefficient of irradiated and un-irradiated regions on the same bar at the same time**



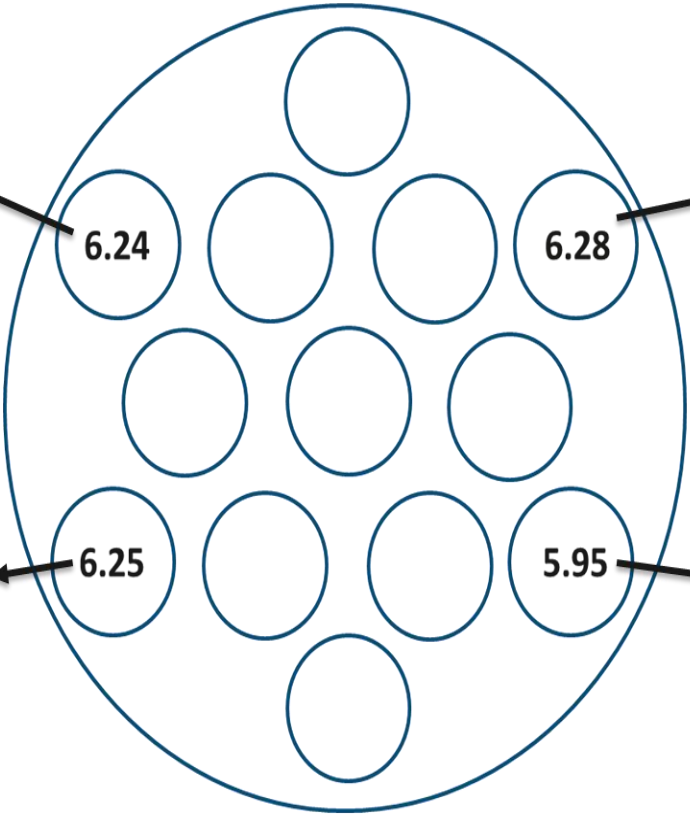
Dashed box shows measurement area

- ~2500 measurements in each region

Gamma irradiation: in-situ resistance testing

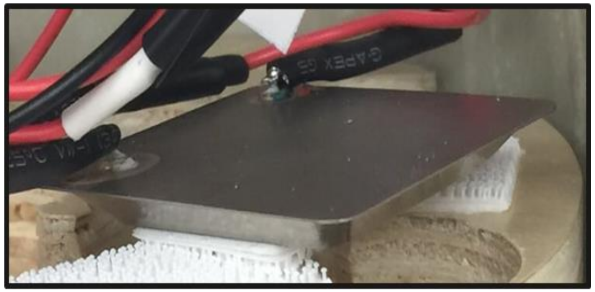
N-Type half-Heusler Bar

Decayed Dose Rate Distribution (kGy/hr)



P-Type half-Heusler Bar

Commercial BiTe Device



half-Heusler Device

Gamma source: Co^{60}