U.S. DEPARTMENT OF ENERGY | Nuclear Energy

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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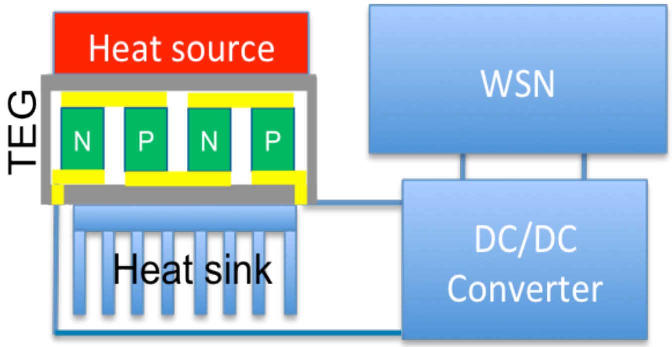
Project Overview

Goal, and Objectives

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

Participants

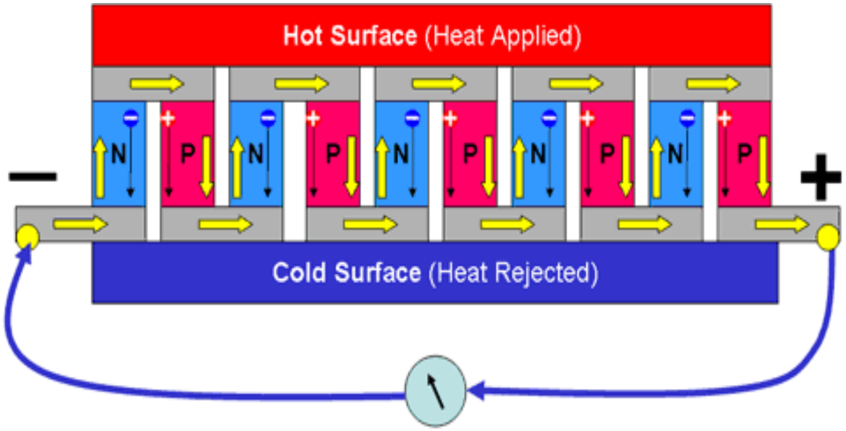
- Yanliang Zhang, University of Notre Dame;
- Brian Jaques, Boise State University;
- Vivek Agarwal, Idaho National Laboratory;
- Zhifeng Ren, University of Houston.



Schedule 01/2015 - 12/2017

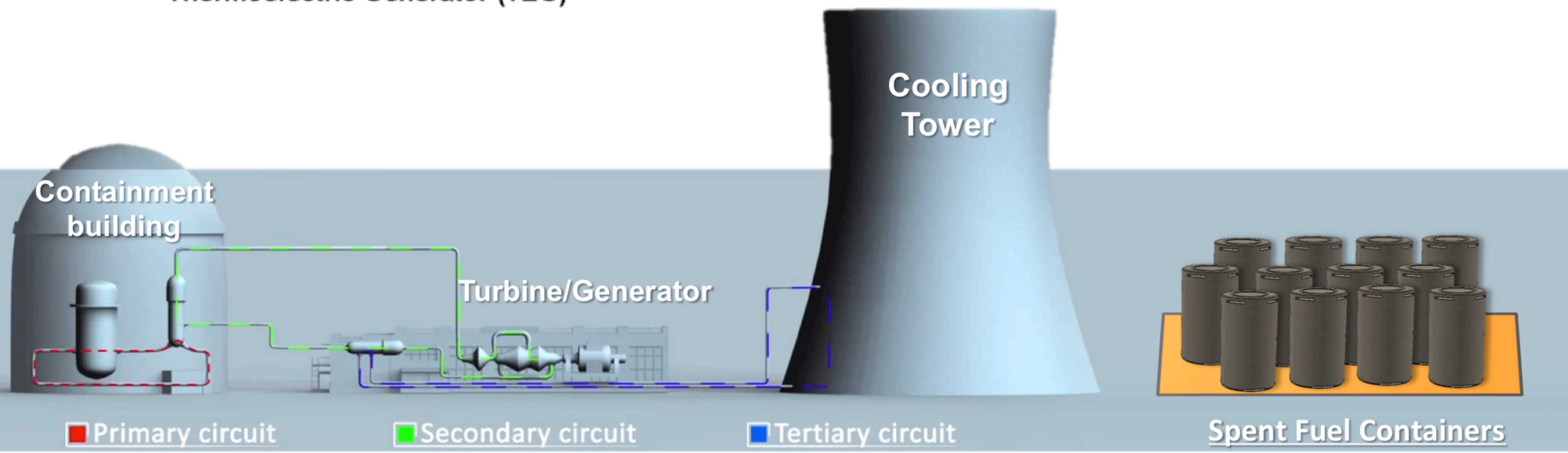
Year 1	• Determine and profile WSN power consumption • Select thermoelectric materials with optimal performance • Study irradiation effect on thermoelectric materials
Year 2	• Develop a TEG and WSN simulator • Design TEG of sufficient power output • Complete analysis of irradiation effect
Year 3	• Fabricate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



Thermoelectric Figure of Merit ZT

Seebeck coefficient

Electrical conductivity

$$ZT = \frac{\alpha^2 \sigma}{\kappa_E + \kappa_L} T$$

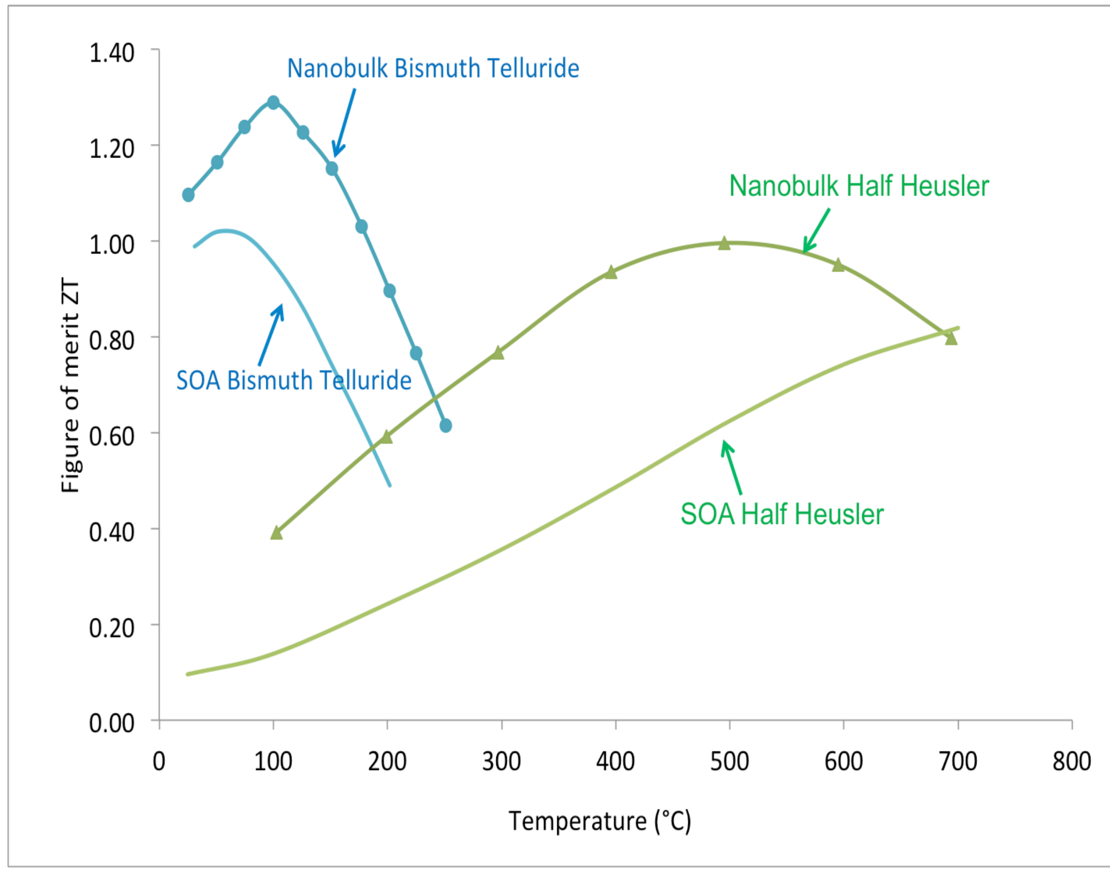
Electronic

Lattice

thermal conductivity

Power factor: $\alpha^2 \sigma$

$$\eta_{\max} = \frac{T_H - T_C}{T_H} \frac{\sqrt{1 + Z\bar{T}} - 1}{\sqrt{1 + Z\bar{T}} + \frac{T_C}{T_H}}$$



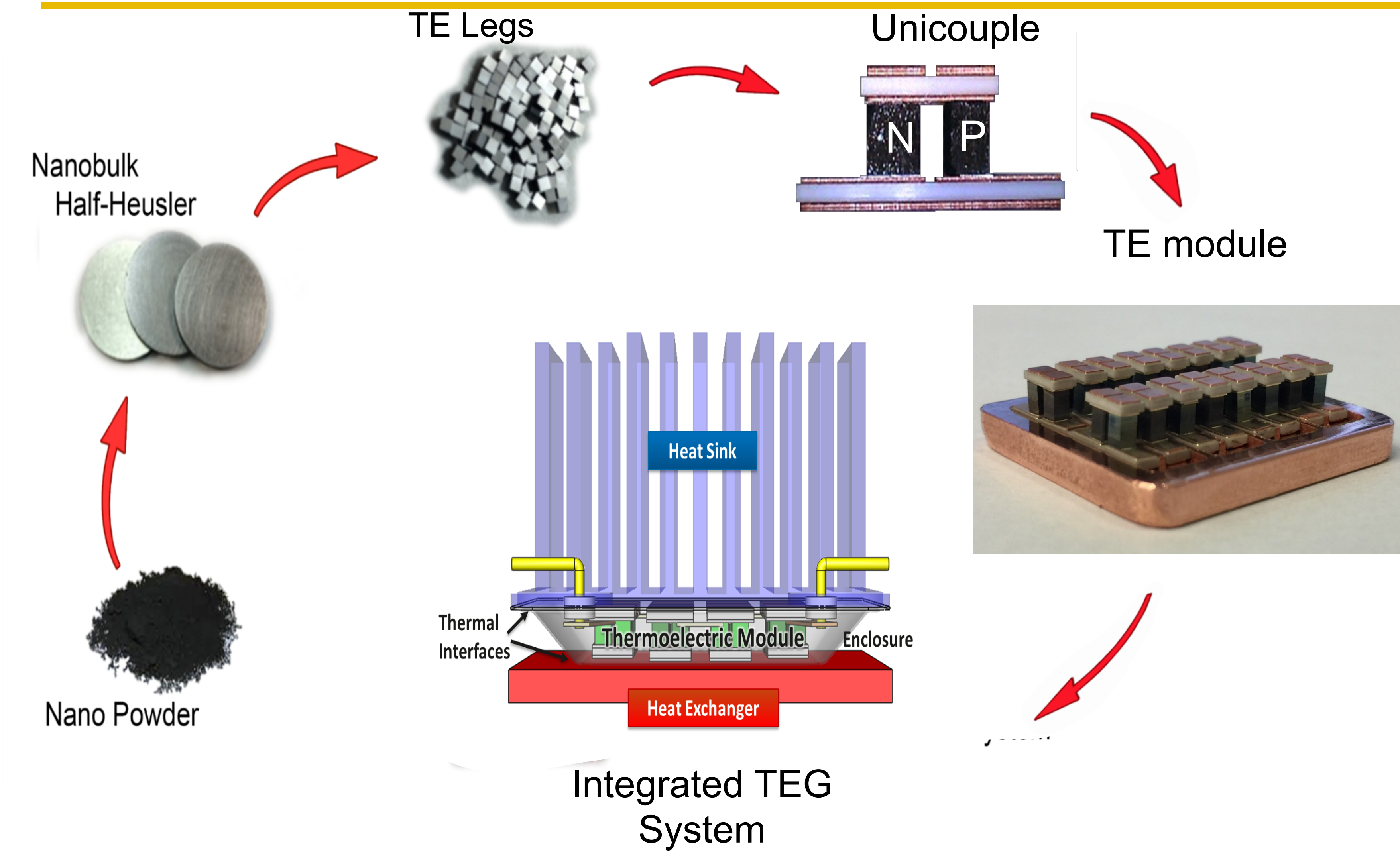
Device efficiency increases with ZT and ΔT

Accomplishments

- **The team achieved the following milestones for FY17**

- 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 and devices
- Demonstrated self-powered wireless sensor system

High-temperature Nanobulk TEG Fabrication Process



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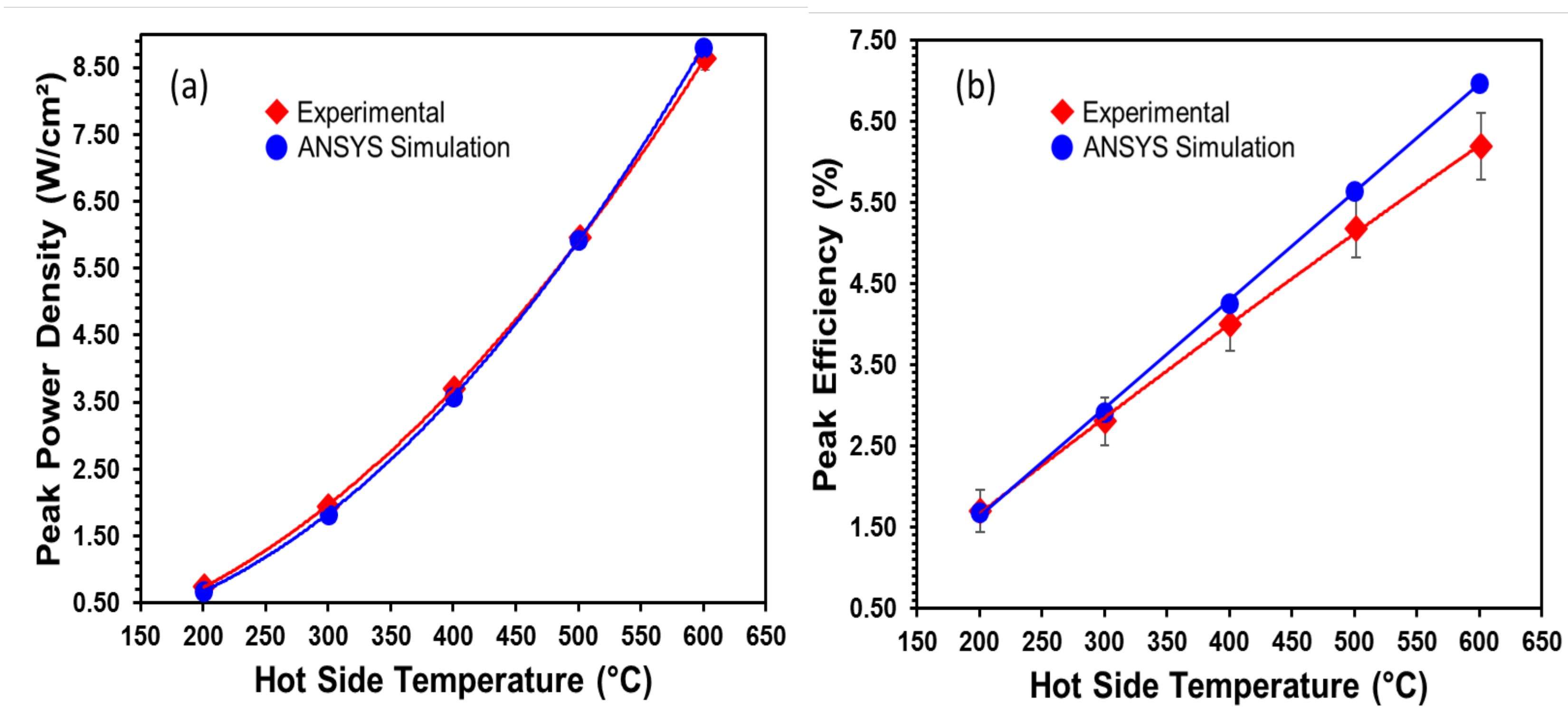
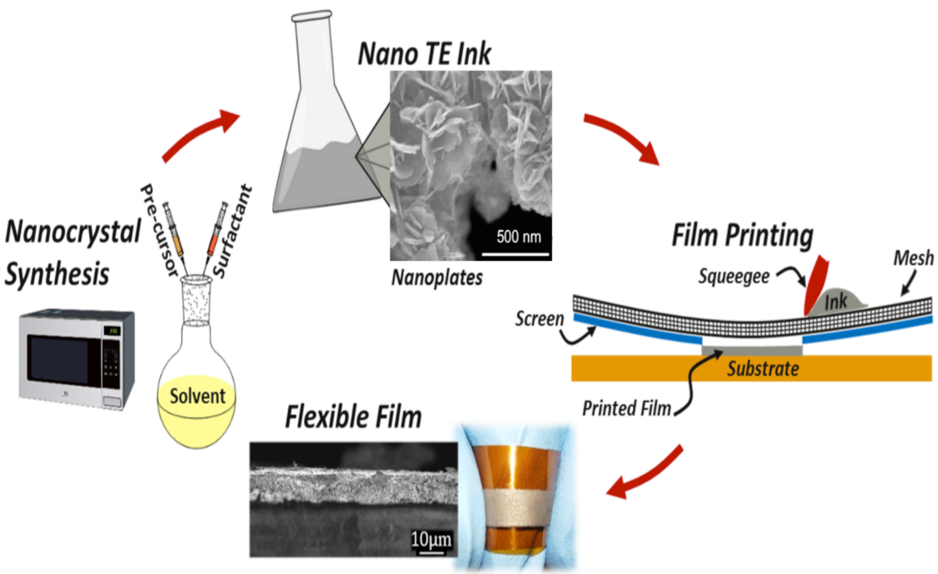
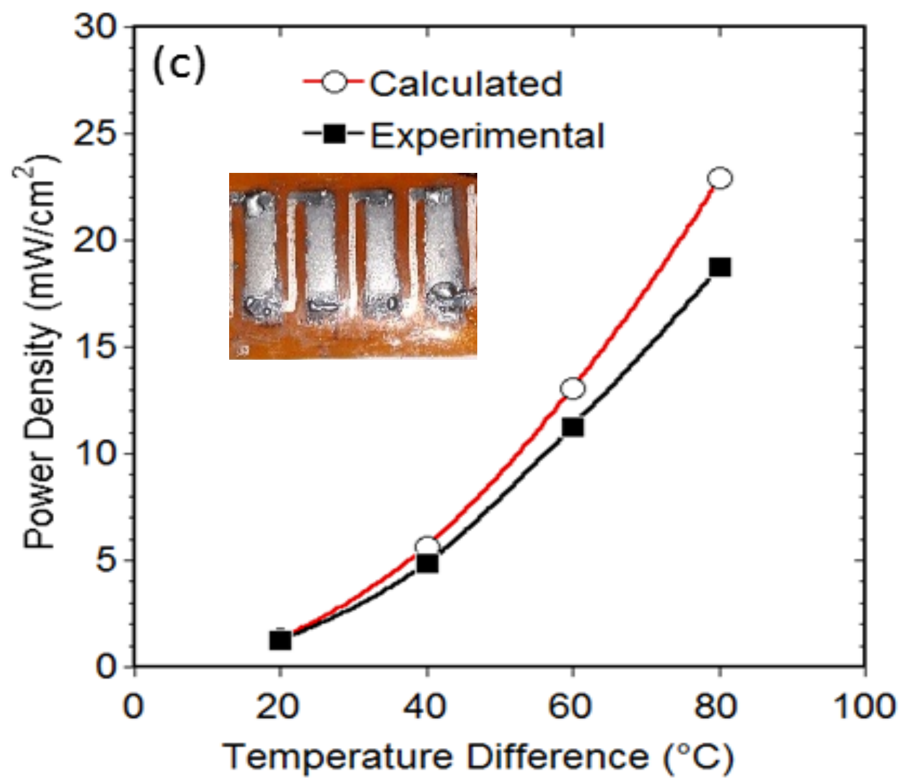
TEG Device Testing Results



- Ultrahigh power density of 8.6 W/cm^2 at 600 ° C and 0.75 W/cm^2 at 200 ° C

Flexible Thermoelectric Generator Fabricated by Additive Printing



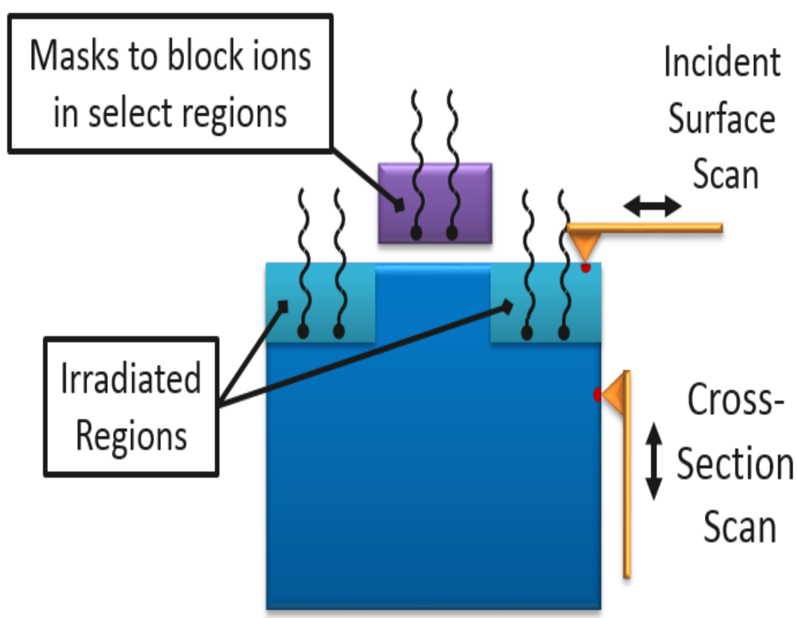


- Developed a novel additive printing process to fabricate flexible TE materials and devices.
- A flexible thermoelectric device produces a power density of 16 mW/cm^2 with 80 ºC ΔT.

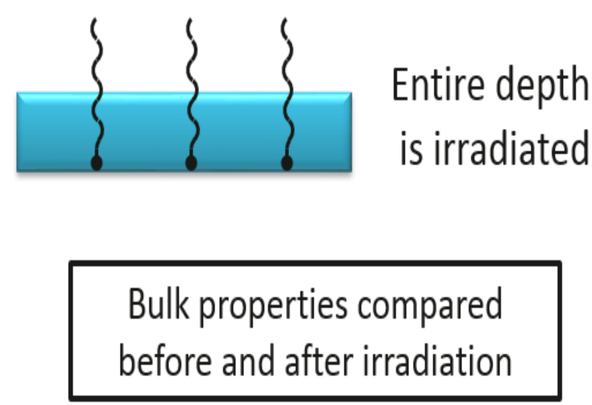
Irradiation Effect on Thermoelectric Materials

- **Ion irradiation to simulate neutron damage:**
  - 2.5 MeV Protons at 100 nA current and $2 \cdot 10^{16}$ ions/cm^2 fluence
- **Two approaches to characterize property changes:**

Approach 1: SThM on Bulk Bar



Approach 2: Thin Film Property Measurement



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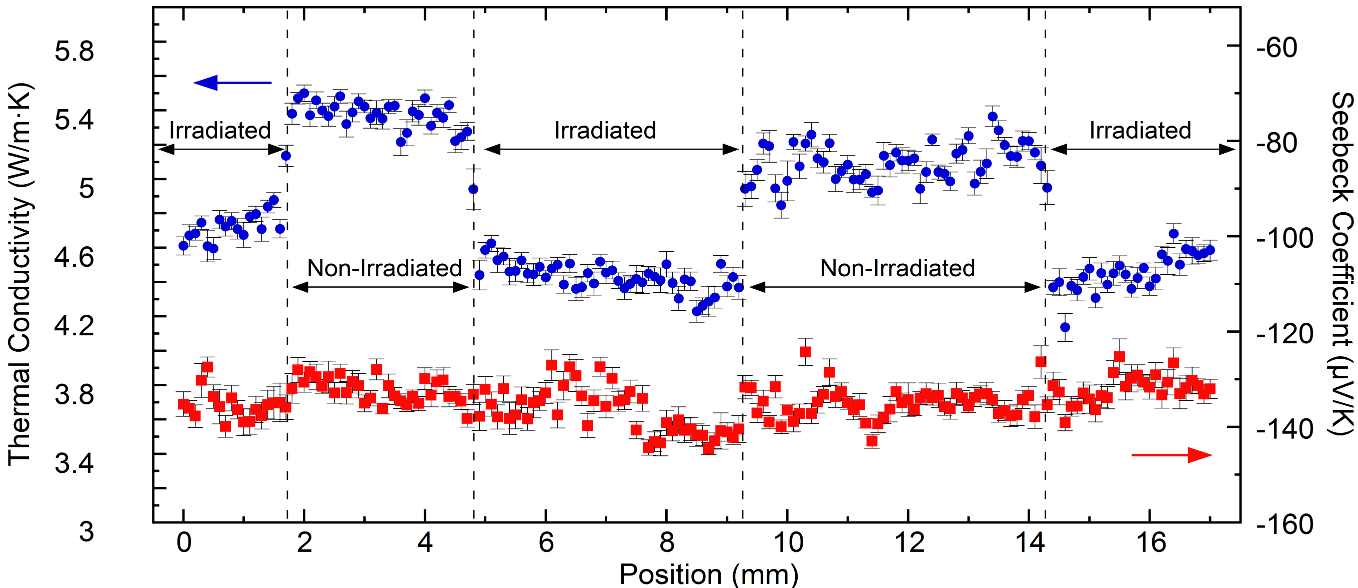
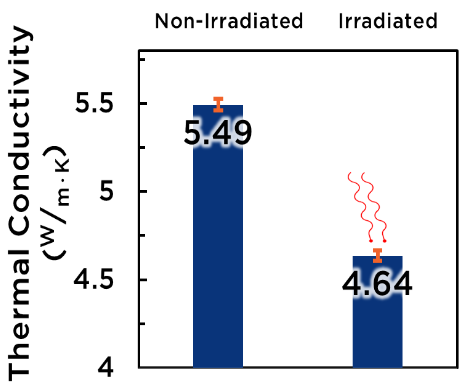
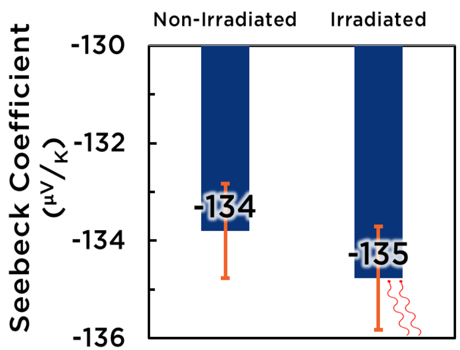
Irradiation Effect on Nanostructured Thermoelectric Materials



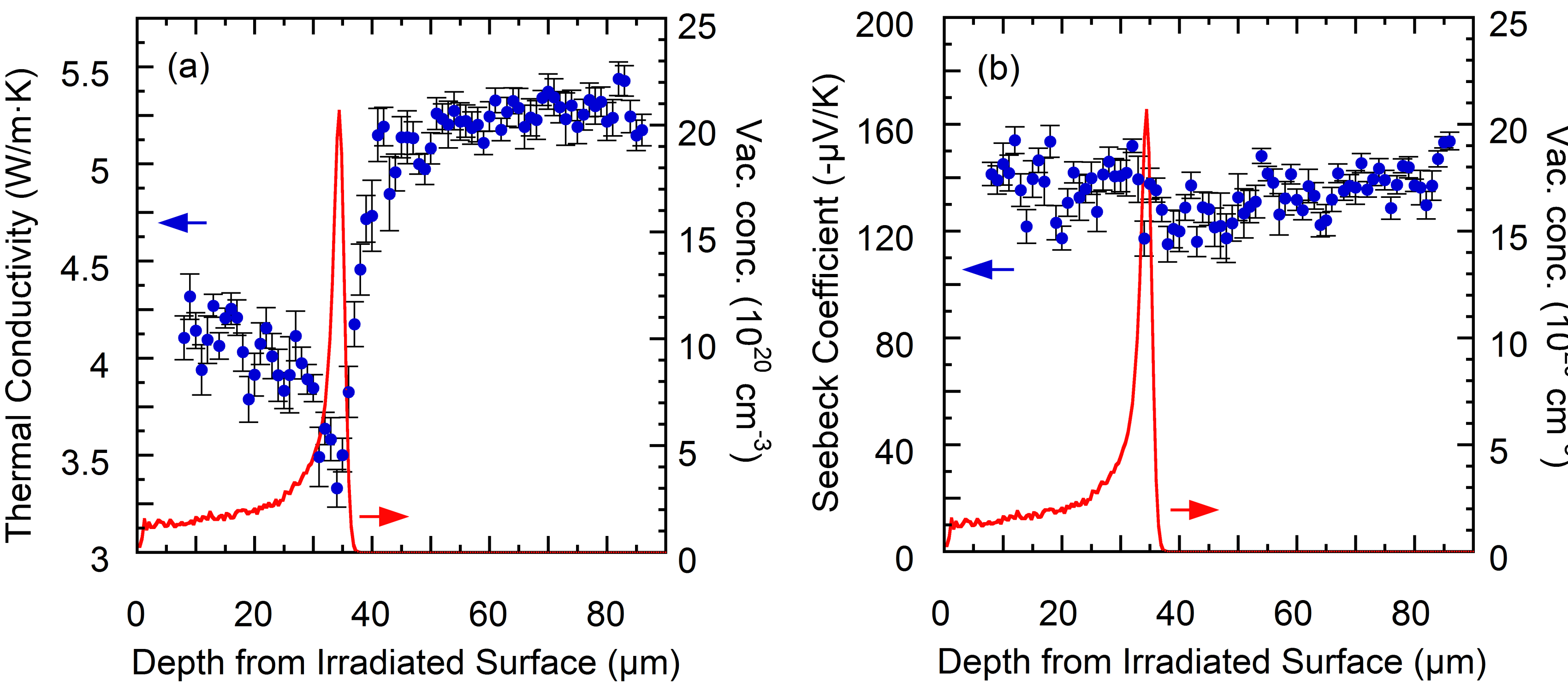




14% decrease in thermal conductivity

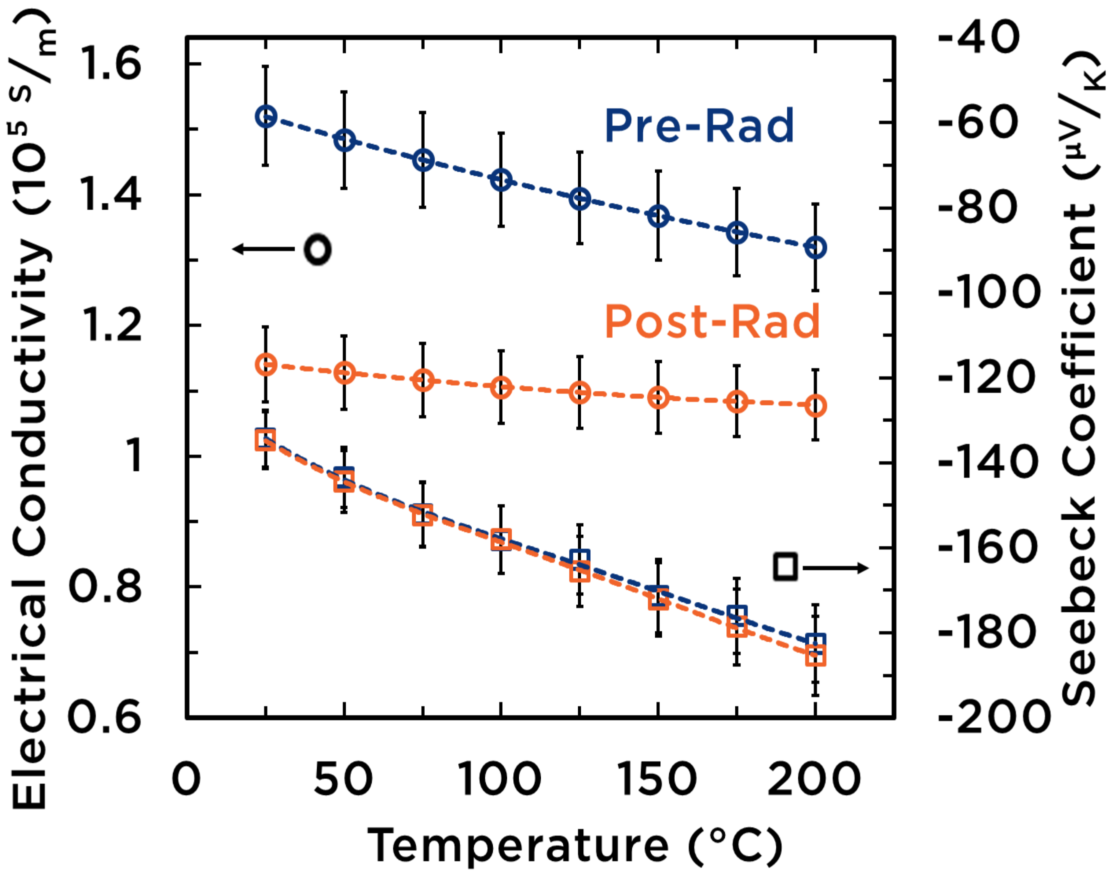
No measurable change in Seebeck coefficient

SThM on Irradiated Cross Section



- Maximum thermal conductivity reduction corresponds to the peak damage location;
- The average thermal conductivity reduces by 25% in the damaged region.

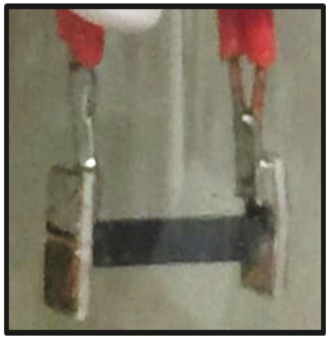
Standard Measurement on Irradiated Film



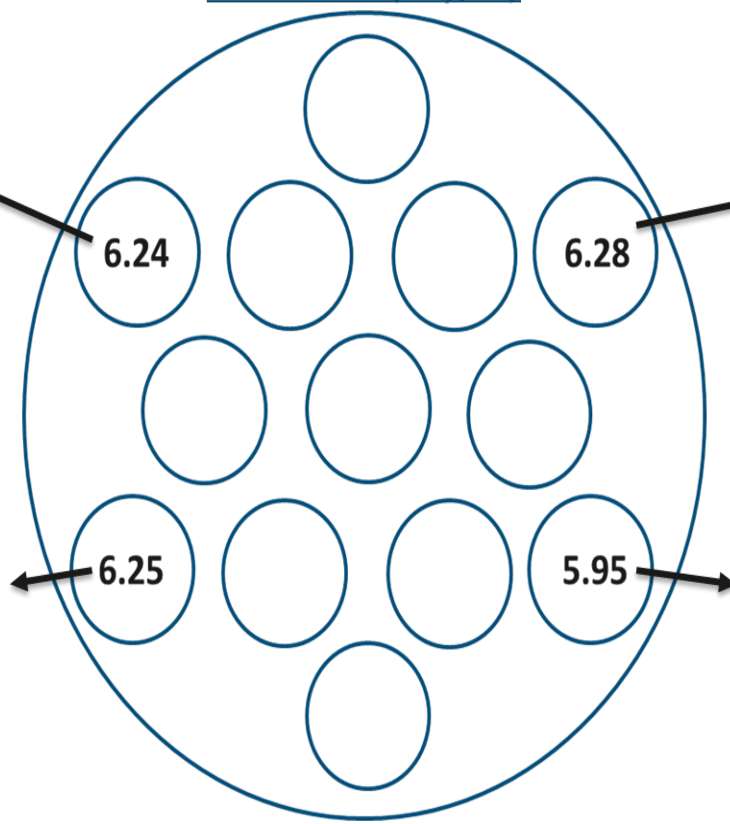
- 25% decrease in both electrical and thermal conductivities at room temperature;
- No change in Seebeck coefficient;
- Room-temperature ZT remains unchanged.

In-situ TEG Device Test During Gamma Irradiation

N-Type half-Heusler Bar

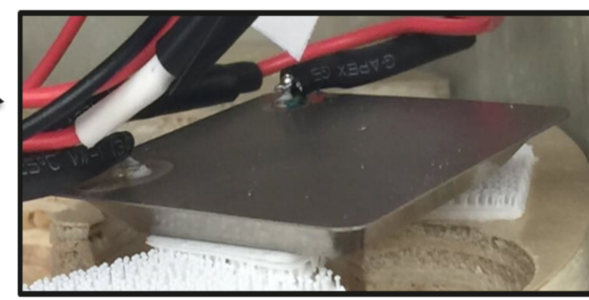


Decayed Dose Rate Distribution (kGy/hr)



P-Type half-Heusler Bar

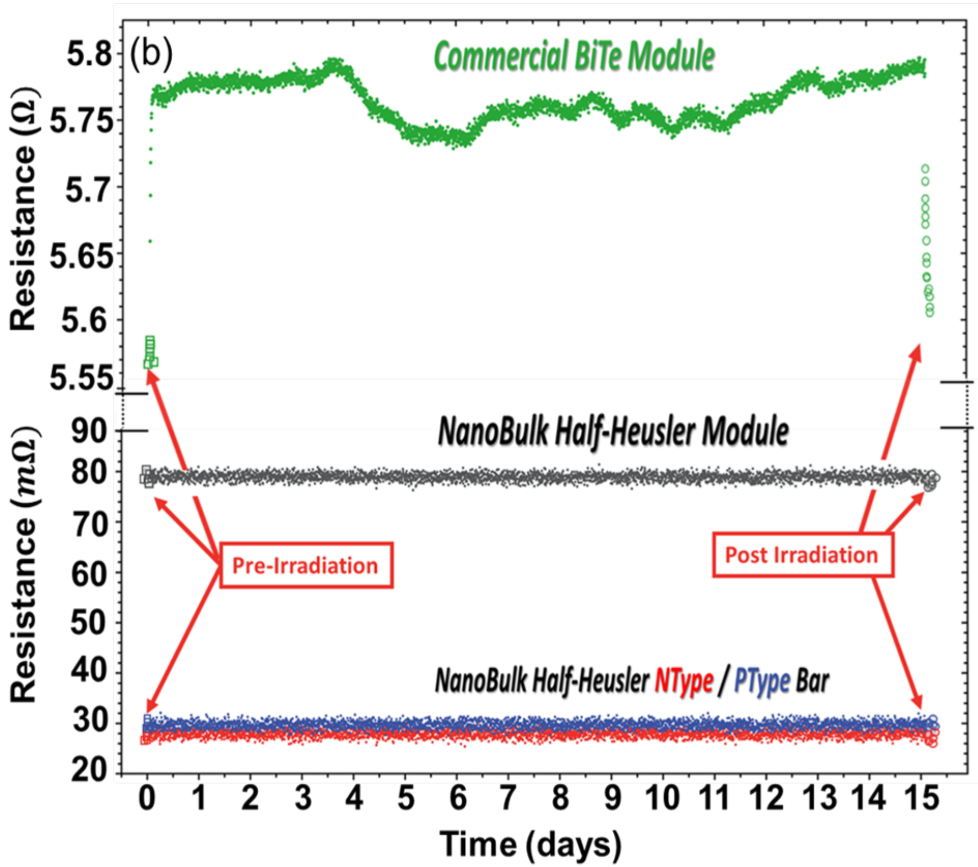
Commercial BiTe Device



half-Heusler Device

Gamma source: Co^{60}

In-situ Test of TEG Devices Under Gamma Irradiation



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

- No measureable change in any nanostructured bulk half-Heusler device

- ~3.5% increase in resistivity of commercial BiTe module

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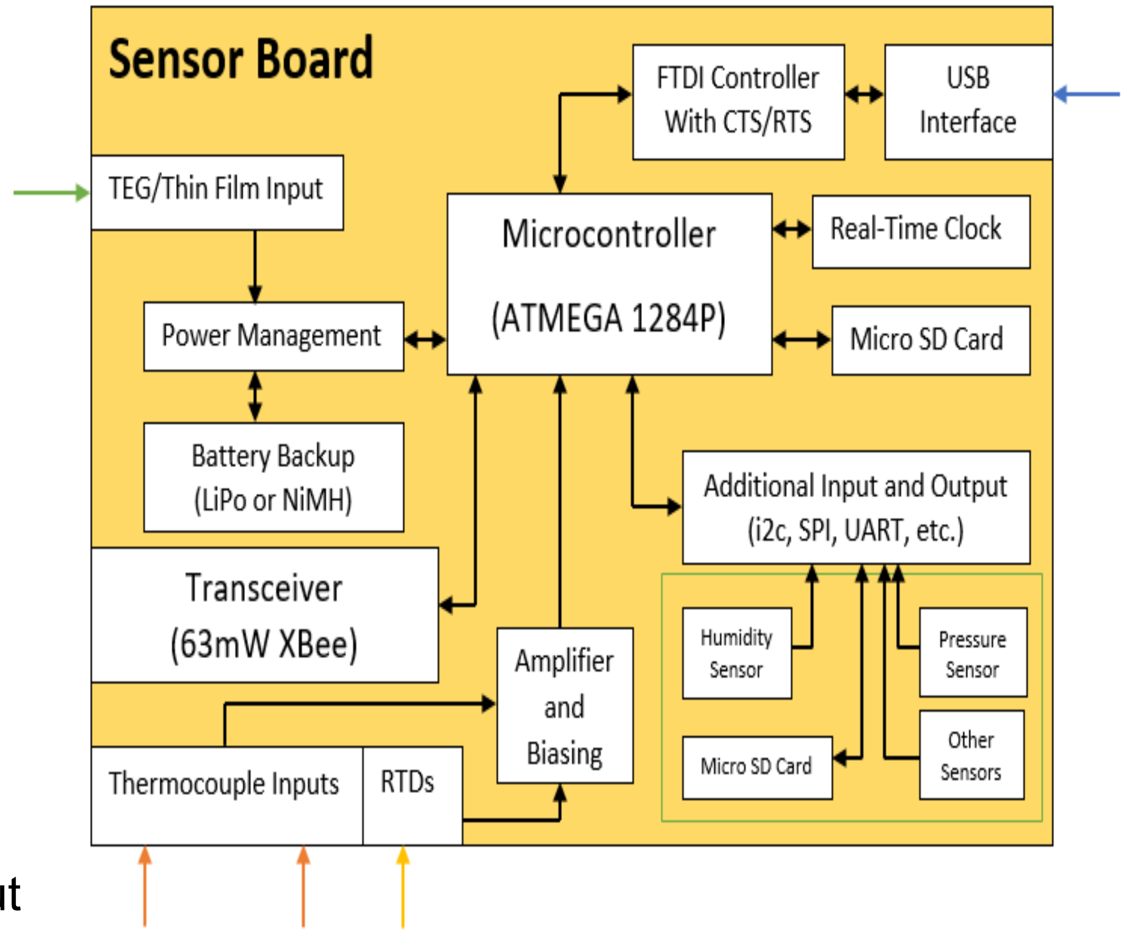
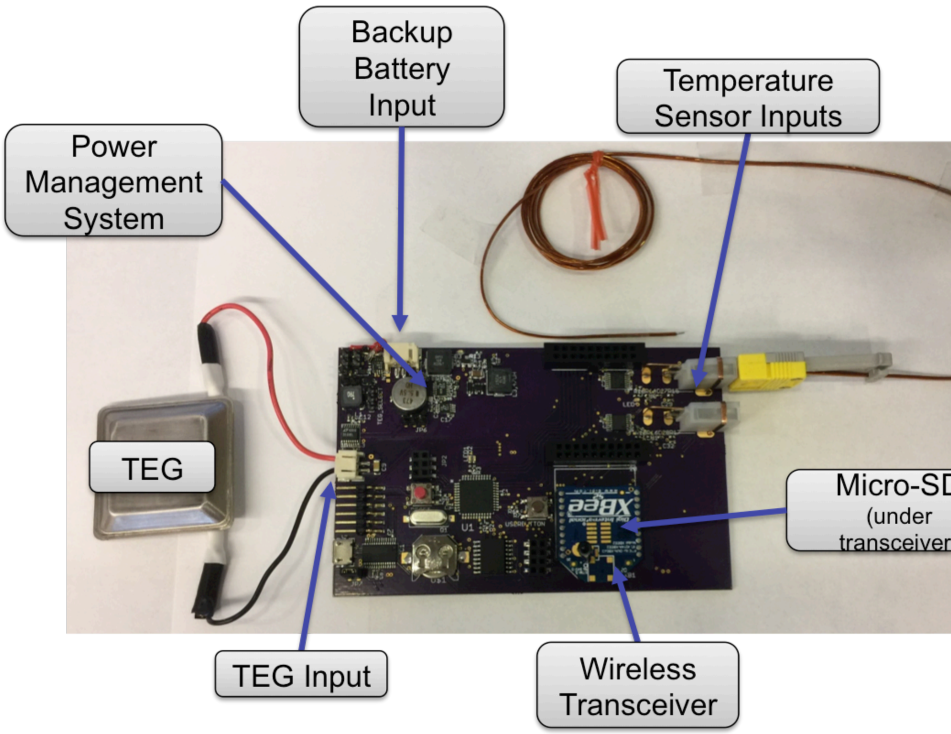
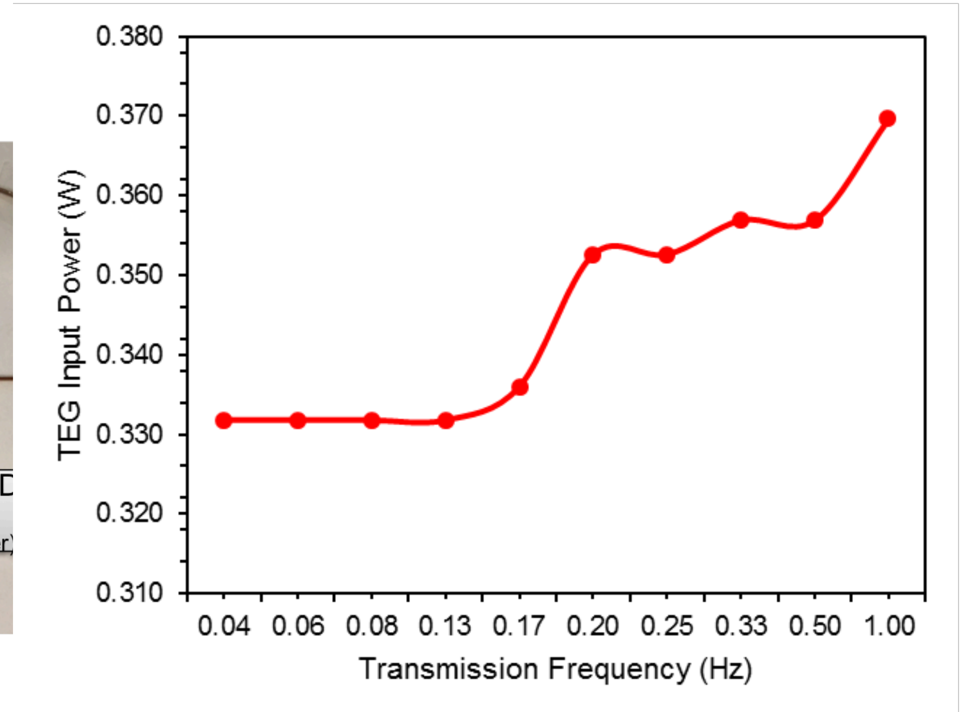
TEG-powered Wireless Sensor System

- Four Main Design Portions:
  - **Power Management System**
    - DC/DC Converter
    - Battery Backup/ Charger
  - **Embedded and Data Storage**
    - Microcontroller
    - USB/FTDI Programming
    - Micro SD Storage
  - **Wireless Transmission**
    - XBee Transceiver
  - **Sensing Inputs**
    - Thermocouple Input
    - Amplifier/Biasing
    - Additional sensor input



TEG-powered Wireless Sensor





- The entire WSN consumes less than 0.4 W, which requires a TEG with <1 cm^2 with 200 ^oC heat source
- More input power is required when frequency of transmission is increased

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.

Conclusion and Future Work

- 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 a self-powered WSN prototype;
- The high-temperature TEGs we developed showed promises for in-pile power harvesting;
- Future work will focus on in-pile testing of the nanobulk TEGs.